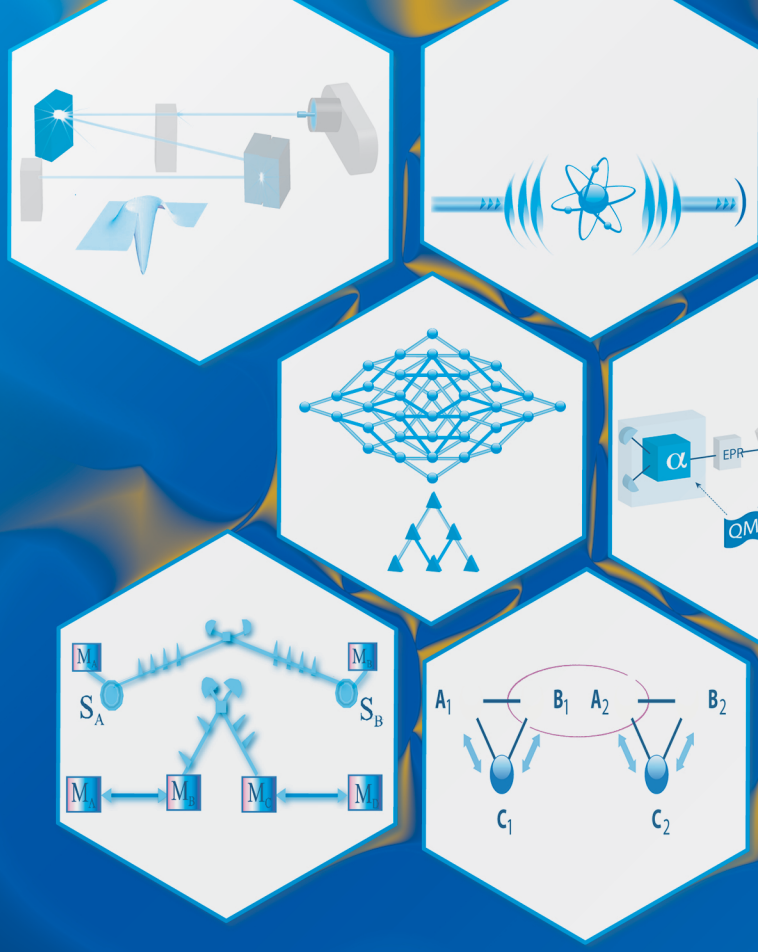
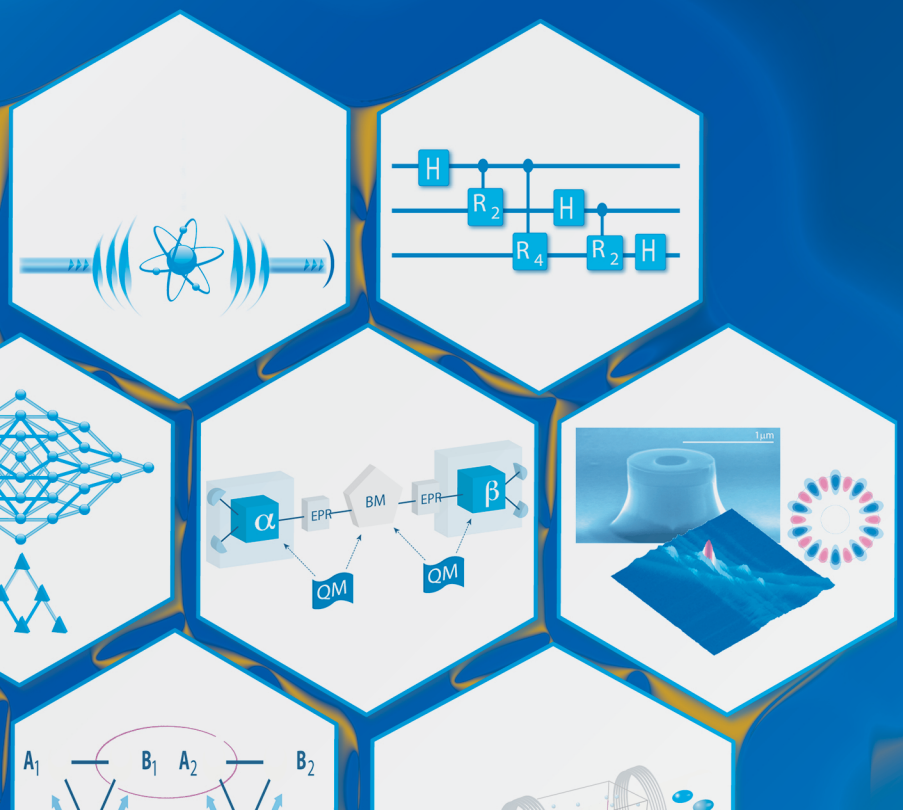
Institute for
Quantum Information Science
at the University of Calgary



QUANTUM FRONTIERS

FINAL ANNUAL REPORT 2012



VISION

To be a world leader in research, teaching, and outreach in pure and applied quantum information science and technology.

MISSION STATEMENT

To conduct world-leading experimental and theoretical research in quantum information;

to provide deep and diverse education and training for senior undergraduate and graduate students;

and to conduct vigorous outreach and service to the public, the University, industry, and the quantum information science community.

KEY FACTS

- **10** postdoctoral fellows
- **49** graduate students
- **8** undergraduate students
- **45** visiting researchers from April to December 2012 including 5 long-term visiting professors and 8 long-term visiting students
- **31** publications in refereed journals & conference proceedings with 5 published in *Physical Review Letters*
- **26** invited talks at national and international conferences/workshops including 1 keynote
- **2.89** million dollars cash income from April to December 2012

CONTENTS

BARRY SANDERS

DIRECTOR'S REPORT

This annual report from the Institute for Quantum Information Science is the final annual report from this Institute, not because the Institute has been terminated but rather because the Institute has successfully germinated a new, larger, more broadly focused incarnation. This new Institute is financially supported by the Innovates Centre for Research Excellence (*i*CORE) unit within Alberta Innovates Technology Futures. This new Institute, which replaces the Institute for Quantum Information Science on 1 January 2013, represents all innovative quantum science and technology taking place at the University of Calgary and will maintain much of the administrative and executive structure of the outgoing Institute.

The new Institute for Quantum Science and Technology in the Faculty of Science will have about one hundred members in contrast to the seventy. Fifteen of these members are professorial and include two *i*CORE Chairs, two Canada Research Chairs (one Tier 1 and one Tier 2), and two Alberta Innovates Scholars plus the 2012 winner of the John C. Polanyi Award of the Chemical Institute of Canada. New research areas under the umbrella of this nascent institute are spectroscopy, quantum-nano research and ab-initio theoretical quantum chemistry.

For administrative reasons, this annual report covers only nine months from 1 April to 31 December 2012 when the Institute for Quantum Information Science ends. Despite only representing three-quarters of a year, the Institute's achievements during this shortened year are quite strong.

As a major annual outreach activity, the Institute holds a Public Lecture, which has been sponsored each year by Alberta Innovates Technology Futures. In 2012, two hundred participants enjoyed Alain Aspect's a wonderful lecture titled "From Einstein's LichtQuanten to Wheeler's delayed choice: wave particle duality for a single photon". Professor Aspect is an internationally acclaimed physicist at the École Polytechnique in Paris and is a pioneer in the foundations of quantum physics and a recipient of the 2010 Wolf Prize in Physics.

The Institute hosted the prestigious annual International Laser Physics Workshop with over 600 participants and co-hosted with the Department of Physics & Astronomy the Canadian Association of Physicists Congress with 600 participants. The Institute has a long-standing history of holding major conferences, which provide the tangential benefit of showcasing the Institute's activities to the broader community.

The Institute also plays a major role in national quantum information networks. Sanders is the principal investigator of the Pacific Institute for the Mathematical Sciences Collaborative Research Group for the Mathematics of Quantum Information, which brings together cognate researchers at the University of Calgary, the University of British Columbia, Simon Fraser University and the University of Washington. CryptoWorks21 is the new NSERC Collaborative Research and Training (CREATE) Program for cryptographic training to meet 21st Century threats, and Sanders is on the Management Committee and also serves as Chair of the Professional Skills Working Group. As for new networks, Simon and Tittel are part of a DARPA network supporting the effort to build a quantum repeater.

In summary the Institute for Quantum Information Science has a lot to be proud of in this nine-month period. Most of the Faculty members are in an early-career stage but have quickly established world-class reputations, and the Institute has played a key role in enabling this rapid progress to superb results and a strong reputation. The new Institute for Quantum Science and Technology can be expected to engender and enable stellar research in quantum areas including quantum information and beyond.

Barry Sanders
Director, IQIS

KEN BARKER

A MESSAGE FROM THE CHAIR

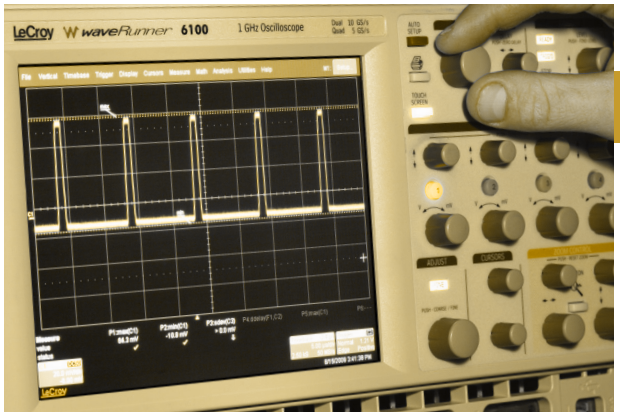
In my final Report from the Chair for the Institute for Quantum Information Science, I would like to commend the Institute Director Barry Sanders and the Institute Administrator Nancy Jing Lu for their outstanding work in making this unit so successful as a research and training centre within the Faculty. The Institute serves as an example and a template not only for the new Institute for Quantum Science and Technology, which will replace it, but also has many excellent practices that the Faculty will incorporate into other Faculty of Science Institutes.

In reading through one biannual and six annual reports since the Institute's inception in 2005 – which are easily accessed from the web page http://www.iqst.ca/shared/reports.php – I am struck by how far the Institute has come since its beginning. The Institute was not simply formed as an aggregation of existing researchers in the Faculty of Science but rather played a key role in seeking and recruiting promising early-career researchers to join the University of Calgary. I can see how the Institute greatly assisted these newly appointed researchers to progress rapidly to having strong research groups and quickly functioning laboratories.

Mentoring served an important role in the Institute's success, especially with research grants and linkage. The Institute also has an enviably strong database and set of web pages that promote the Institute's strengths and successes well beyond the University of Calgary's boundaries. Finally I note that the Institute has a lean but highly effective administrative team that delivers crucial support to researchers, postdocs and students so that they can channel their energy to delivering high-quality scientific results.

The University of Calgary's strength and reputation has benefitted from the prowess of its quantum information team. The Faculty of Science is looking forward to seeing the Institute broaden to nurture and support all quantum research areas in the Faculty.

Ken Barker
Chair of the Board of Directors, IQIS



HIGHLIGHTS OF 2012

Research Achievements

The Institute for Quantum Information Science enjoyed excellent achievements between April and December 2012. Foremost among these achievements was the award from the Alberta Ingenuity Fund of $150,000 each year for three years to support developing and sustaining a new Institute for Quantum Science and Technology. This new Institute will add seven more Faculty Members, from Physics and Chemistry, to the eight Faculty Members from the former Institute for Quantum Information Science.

Some of the Institute's high-profile research has received significant public attention. There was extensive media coverage of a Physical Review Letters proposal by Christoph Simon and Wolfgang Tittel and student Sadegh Raeisi to circumvent the no-cloning theorem of quantum mechanics. Their strategy is to clone, and then un-clone, so to speak, a photon. This proposal would enable tests of still-contentious micro-macro entanglement. In fact, subsequent to this micro-macro entanglement proposal, Alex Lvovsky and Christoph Simon and their groups demonstrated micro-macro entangled light experimentally with one photon in the micro state and more than a hundred million photons in the macro state.

The proposal for microwave-controlled on-demand microwave pulse storage and release, developed by Barry Sanders and postdoctoral researcher Patrick Leung and published in Physical Review Letters, was a highlighted achievement in Superconductor Week. This scheme provides a blueprint for controlling microwave fields entirely within the superconducting circuit without the need for coupling other materials, which can introduce inefficiencies in the architecture.

Christoph Simon collaborated with University of Waterloo researchers on an experiment that generalized the famous Einstein-Podolsky-Rosen paradox, which originally clarified the completeness problem of quantum theory. This new experiment extrapolated from the original case of two particles that are quantum correlated via a continuous parameter to the case of three entangled particles, thereby opening the door to new and exciting tests of quantum mechanics. This Nature Physics paper was reported by the popular site Science 2.0.

The Institute is proud of its many achievements, which are too numerous to mention here. In addition to the breakthroughs discussed above, a few more results deserve special attention.

Paul Barclay's Nanoscale Quantum group, jointly located at the University of Calgary and at the National Institute for Nanotechnology (NINT), collaborated with NINT and University of Alberta to demonstrate a torsional sensor with unprecedented sensitivity, which was featured on an Applied Physics Letters cover and was highlighted by Nature.

In an IEEE Transaction on Information Theory paper, Gilad Gour and collaborator Shmuel Friedland addressed the important quantum information theory problem of whether entanglement between signal states can assist transmission of classical information through quantum channels. They showed that only a high degree of entanglement is enabling.

Barry Sanders collaborated with researchers from Singapore's Agency for Science, Technology and Research and from Lakehead University to show that the recently proposed purpose-built problem-specific photonic quantum computer for efficiently solving the classically intractable boson sampling problem is in fact computing functions immanants rather than computing permanents, which are a special case of immanants. Only in the unattainable ideal of simultaneous input photons does the permanent emerge, but Sanders and collaborators show how to program this quantum computer to recover the permanent and more.

Awards

INTERNATIONAL AWARDS

CARLSBERG FOUNDATION AWARD (DENMARK)
Daniel Oblak

CHINESE TOP UNIVERSITY GRADUATE STUDENTS STUDYING ABOARD SCHOLARSHIP (PEOPLE'S REPUBLIC OF CHINA)
Jiying Zhang (ended September 2012)

KING SAUD UNIVERSITY AWARD (SAUDI ARABIA)
Khulud Almutairi

PAAET AWARD (KUWAIT)
Hessa Alotaibi

NATIONAL AWARDS

EMERGING LEADERS IN THE AMERICAS PROGRAM (ELAP)
Jhon Lozada Vera (ended July 2012)

IZAAK WALTON KILLAM MEMORIAL SCHOLARSHIP
Joshua Slater

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP – DOCTORAL
Connor Kupchak (ended August 2012)
Neil Sinclair
Joshua Slater
Marcelo Wu

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP – MASTER
Edouard Pelchat (ended August 2012)

NSERC POSTGRADUATE SCHOLARSHIP – DOCTORAL
Andrew MacRae (ended April 2012)

NSERC USRA PROGRAM
Michael Briscoe
Jeff Maki

PIMS POSTDOCTORAL FELLOWSHIP
Vlad Gheorghiu
Collin Trail

PROVINCIAL AWARDS

ALBERTA INNOVATES GRADUATE STUDENTS SCHOLARSHIP
Adam D'Souza (ended August 2012)
Connor Kupchak (ended August 2012)
Andrew MacRae (ended April 2012)
Neil Sinclair
Joshua Slater (ended August 2012)
Michael Underwood (ended August 2012)
Marcelo Wu

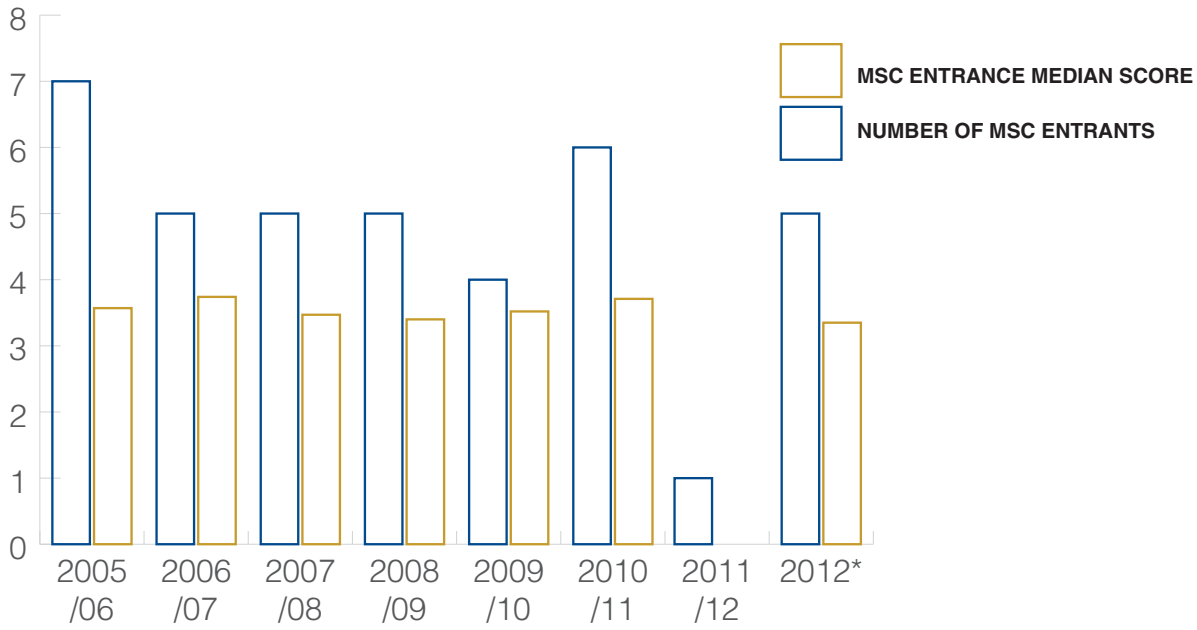
UNIVERSITY OF CALGARY AWARDS

QUEEN ELIZABETH II GRADUATE SCHOLARSHIP
Ish Dhand
Mark Girard
Khabat Heshami
Edouard Pelchat
Adarsh Prasad
Erhan Saglamyurek
Tian Wang

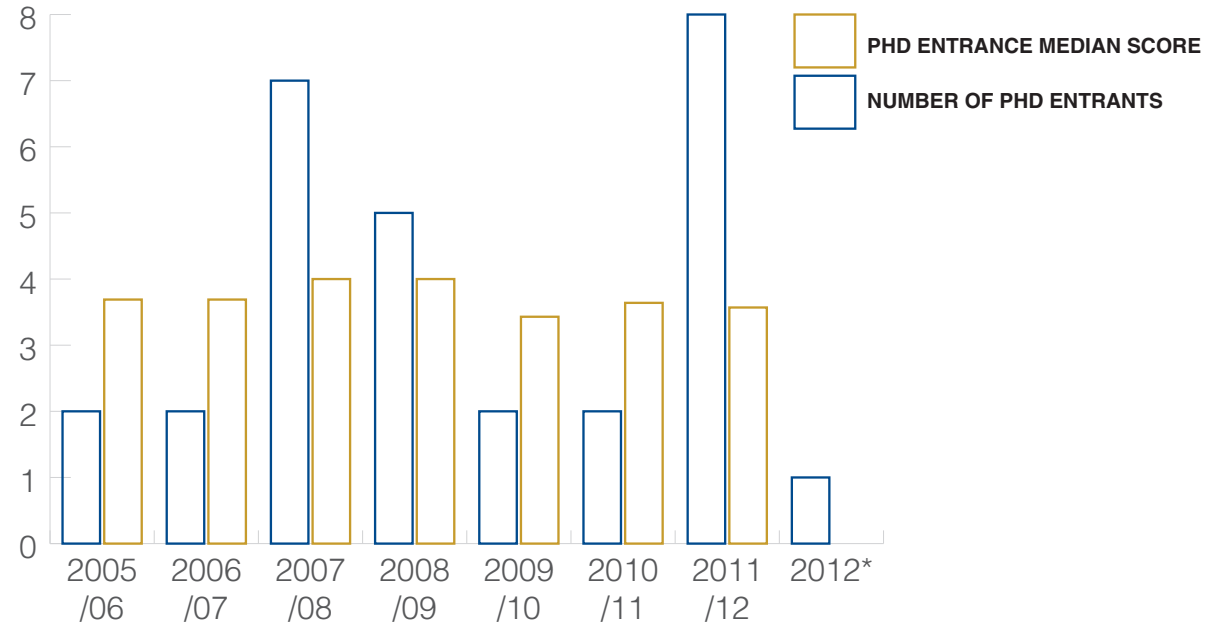
Key Performance Indicators

* Information provided for 2012 is for the period of 9 months from April to December 2012

GRADUATE STUDENTS ENROLMENT AND QUALITY OF ENTRANTS[1,2,3]

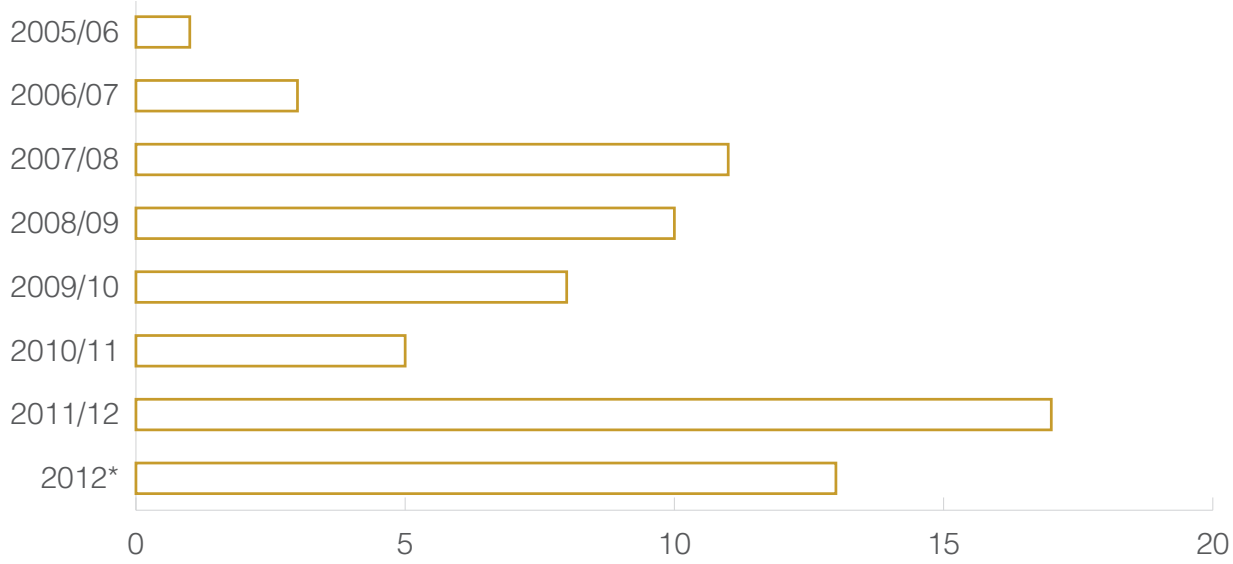


[1] One MSc student registered in the year 2011/12, but, for confidentiality, the entrance score is not revealed.
[2] Median MSc GPA decline is largely due to admission of several students from India where GPAs are typically low compared to those of other countries.

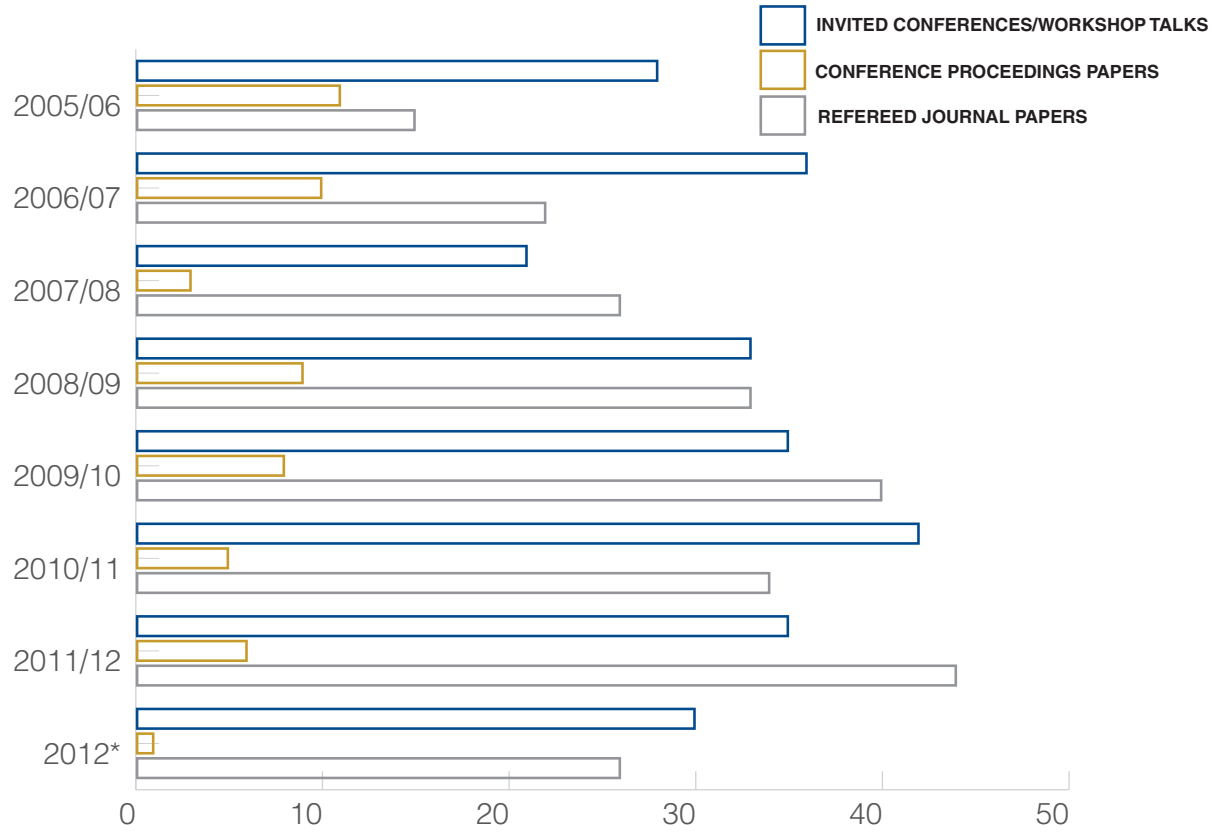


[3] One PhD student registered in September 2012, but, for confidentiality, the entrance score is not revealed.

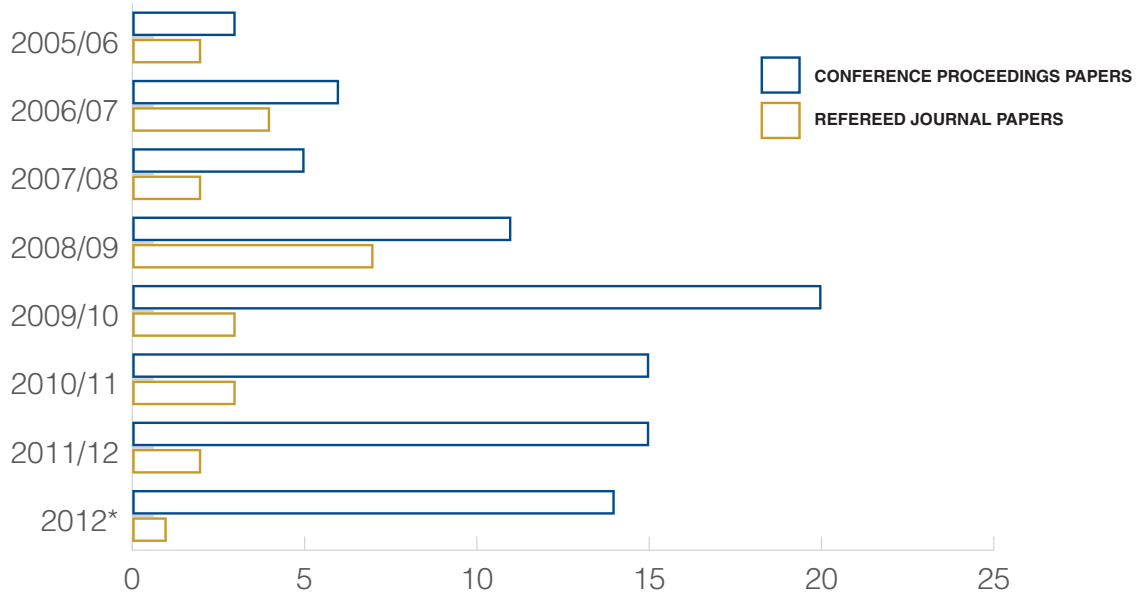
UNDERGRADUATE PROJECTS



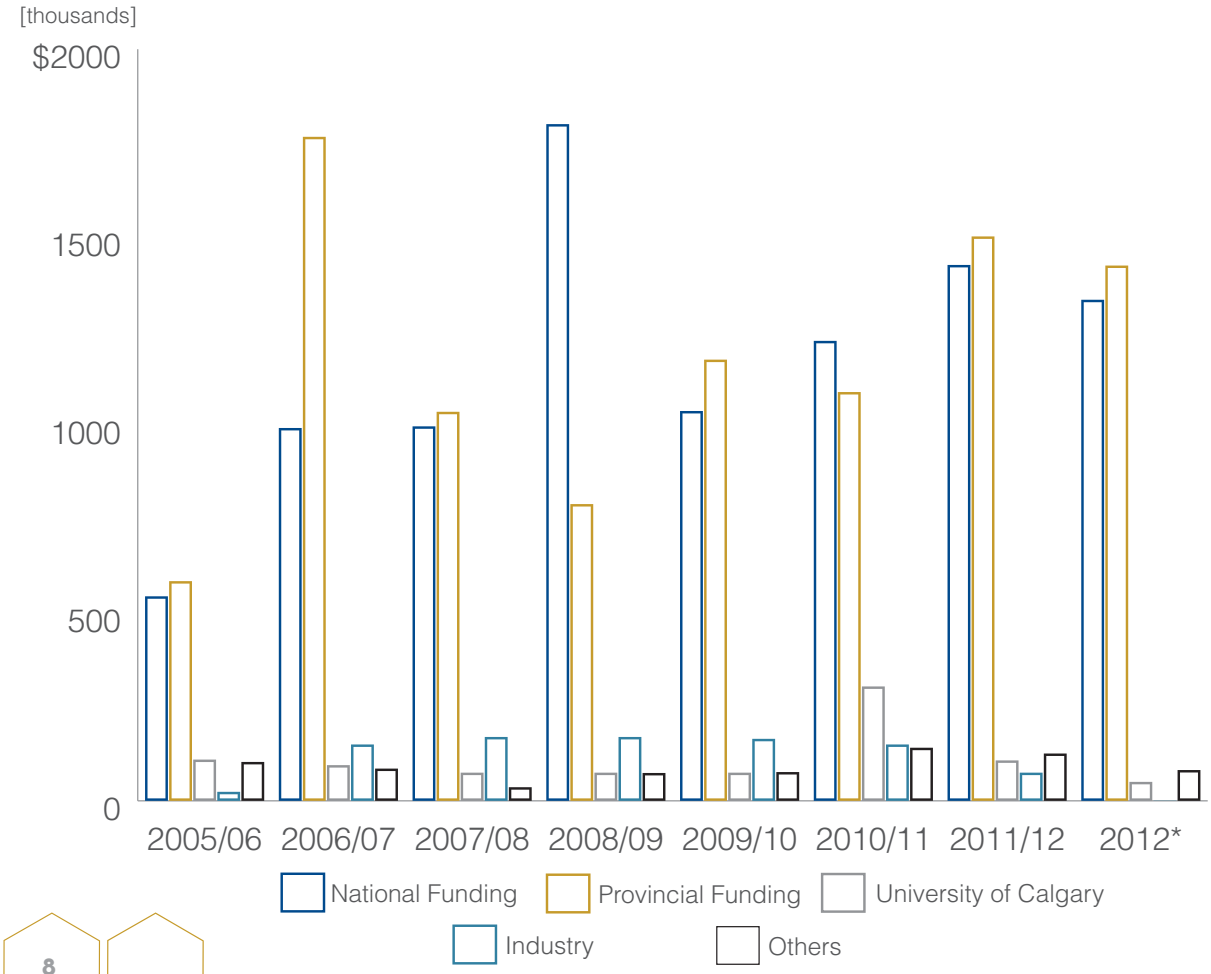
PUBLICATIONS AND PRESENTATIONS



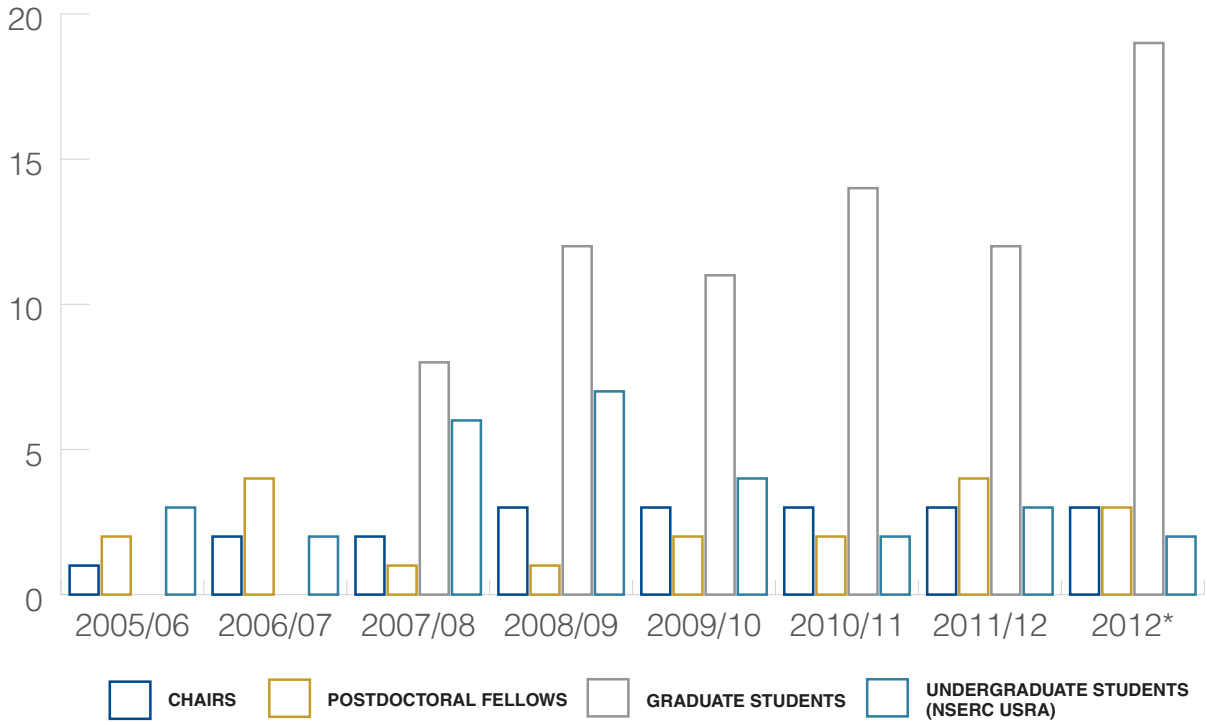
PUBLICATIONS WITH IQIS STUDENT AS FIRST AUTHOR AND CO-AUTHOR



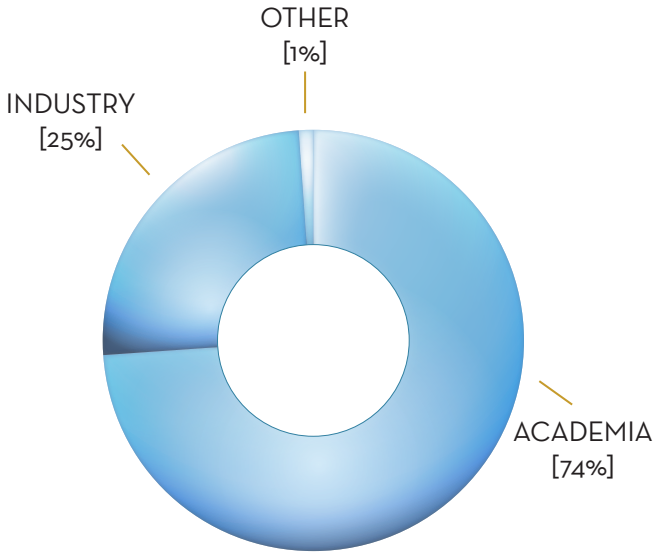
REVENUE (UNAUDITED)



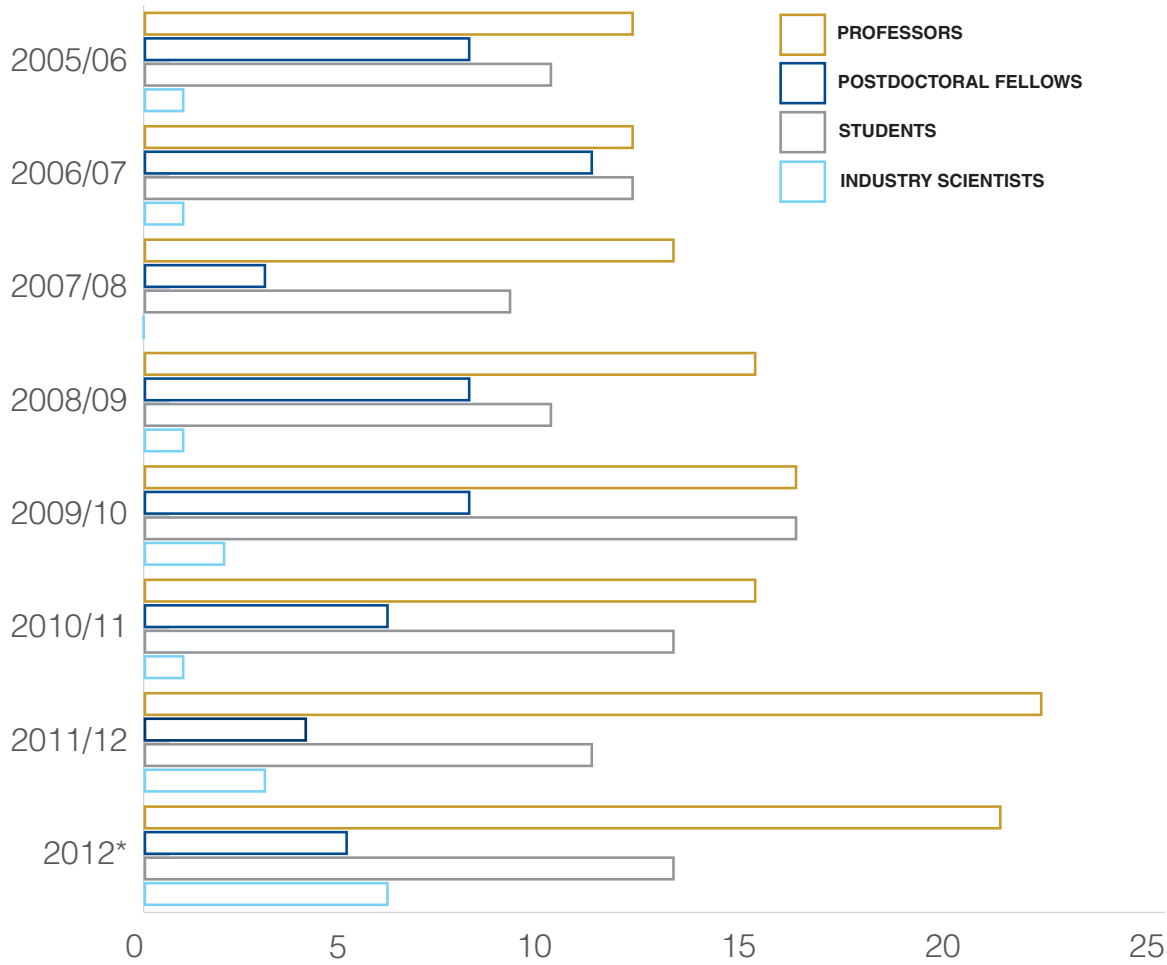
EXTERNAL AWARDS (CHAIRS, FELLOWSHIPS AND SCHOLARSHIPS)



IN THE WORKFORCE AND ACADEMIA



VISITORS


2005/06
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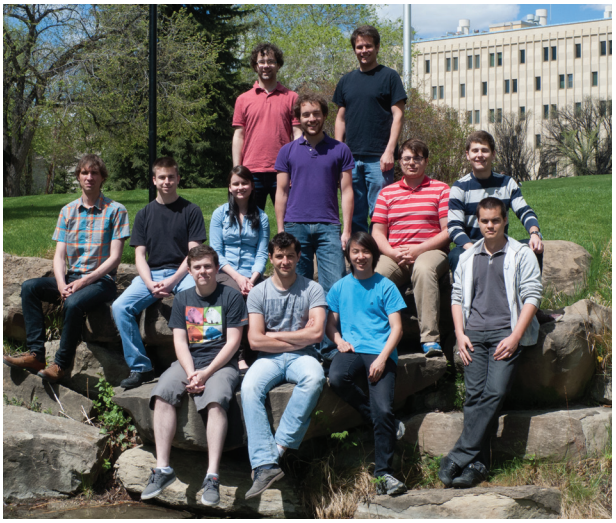
20
25
PROFESSORS
POSTDOCTORAL FELLOWS
STUDENTS
INDUSTRY SCIENTISTS

DESTINATIONS OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS AFTER LEAVING IQIS

RESEARCH GROUPS



Nanoscale Optics

DR. PAUL BARCLAY

Our research studies interactions between light and nanoscale systems such as single atoms, electron spins and nanomechanical structures. Using nanofabrication methods to engineer the optical properties of these systems, it is possible to dramatically enhance light-matter coupling, opening the door to experiments that use light to delicately measure and transmit information describing the dynamics of nanoscale quantum systems.

Our current focus involves coupling single quantum emitters, or “artificial atoms” to optical nanocavities. These quantum emitters are formed by impurities in materials such as diamond, whose quantum state is useful for storing information and sensitively probing magnetic fields. This research has applications in quantum information processing, developing low power optical devices, and creating sensitive and compact environmental sensors.

We have labs at both the University of Calgary and the NRC National Institute for Nanotechnology (NINT) located in Edmonton, providing access to advanced nanofabrication tools and close contact with leading quantum optics and nanotechnology researchers.

Practical Approaches to Quantum Computation

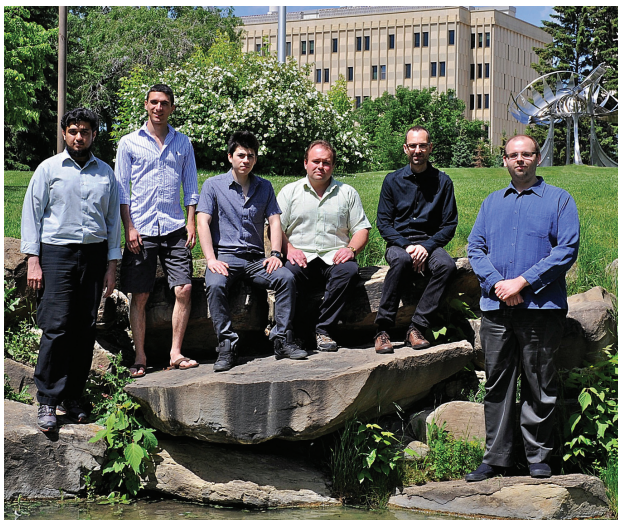
DR. DAVID FEDER

Quantum computers have the potential to solve problems more efficiently than the best-known classical computers, but so far only very small, proof-of-principle quantum computers have been built. The research of our group is focused mainly on understanding how the intrinsic properties of physical systems, such as ultracold atomic gases or spin lattices, can be employed to construct larger devices able to perform quantum computation. In the process, we are exploring alternative models for the implementation of quantum logic, such as one-way quantum computation, quantum walks, and topological quantum computation.

Quantum Information Theory

DR. GILAD GOUR

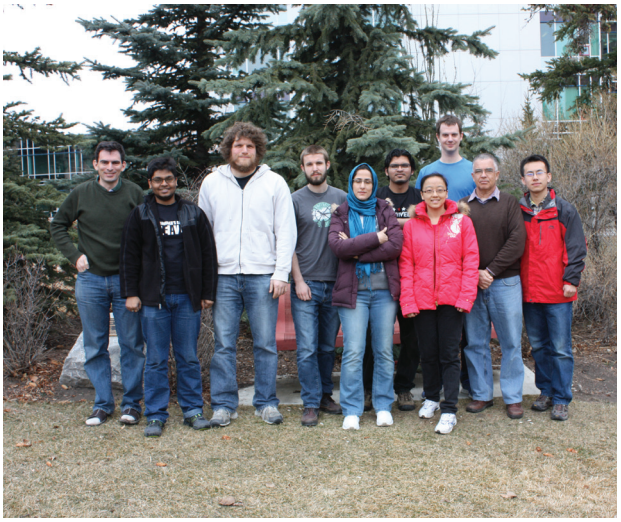
The quantum information group in the Department of Mathematics and Statistics conducts research on the mathematics of quantum information. Theoretical research in quantum information relies on sophisticated mathematical methods, such as algebraic geometry, matrix analysis, group theory and C*-algebras. The goal of our group is to use the knowledge in these fields to solve core problems in quantum information science.



Quantum Computing

DR. PETER HØYER

The quantum computing research group within the Department of Computer Science conducts research in computational aspects of quantum mechanical systems. Quantum computers are in particular interesting because they offer a possibility to achieve computations that cannot be easily achieved on traditional computers. We utilize the potential powers of quantum systems to develop quantum algorithms, quantum communication protocols, quantum cryptographic protocols, and quantum computer simulations of quantum mechanical systems. We conduct work on characterizing these powers and their limitations by studying quantum complexity theory, non-locality, entanglement, and quantum information theory.



Quantum Information Technology with Light and Experimental Quantum Optics

DR. ALEX LVOVSKY

Photons are excellent carriers of quantum information. One can build an entire quantum information processor by means of single-photon sources, detectors, and simple linear optical elements such as mirrors and beam splitters. Our group concentrates on implementing light for the purposes of quantum information technology – that is, learning to synthesize, control, characterize, store arbitrary quantum states of the electromagnetic field, as well as bring photons into interaction with each other.

Quantum Information Science

DR. BARRY SANDERS

Our aim is to develop quantum information technologies that have transformative applications and will be feasible within a decade. The research program is divided into five strands: (i) long-distance secure communication, (ii) simulations of complex systems, (iii) implementations of quantum information tasks, (iv) empirical characterization of quantum states and processes, and (v) determining and quantifying all resources for quantum information processing.

Theoretical Quantum Optics

DR. CHRISTOPH SIMON

The interaction of light and matter at the quantum level played a major role in the development of quantum physics. Its detailed study in the field of quantum optics has led to the development of important applications such as the laser, and to the first experimental demonstrations of the most striking features of quantum physics, such as entanglement and quantum non-locality. However, quantum optics is not ready to rest on its laurels. There are two key future challenges. On the one hand, we strive to develop genuine applications of these fundamental quantum features. Our group is particularly interested in the development of quantum repeaters, which will be essential for long-distance quantum communication. This motivates us to study potential implementations of quantum memories and of quantum gates between individual photons in various systems. On the other hand, quantum optical systems are ideally positioned to explore the quantum-classical transition, allowing us to deepen our understanding of how the classical macroscopic world arises out of microscopic quantum behaviour. This motivates us to study the quantum amplification of photons to macroscopic levels, as well as quantum opto-mechanical systems.

Quantum Cryptography and Communication

DR. WOLFGANG TITTEL

Photons and atoms are key constituents for long-distance quantum communication and quantum networks. Our group's effort focuses on building photon-based quantum cryptography systems through optical fibres and targets the development of a quantum repeater to extend quantum cryptography past its current distance limit. This includes developing novel techniques for rendering photonic quantum communication primitives such as quantum teleportation practical, plus hitherto unrealized means for efficient and reversible transfer of quantum information between photons and atoms for temporal storage.

MANAGEMENT AND MEMBERSHIP

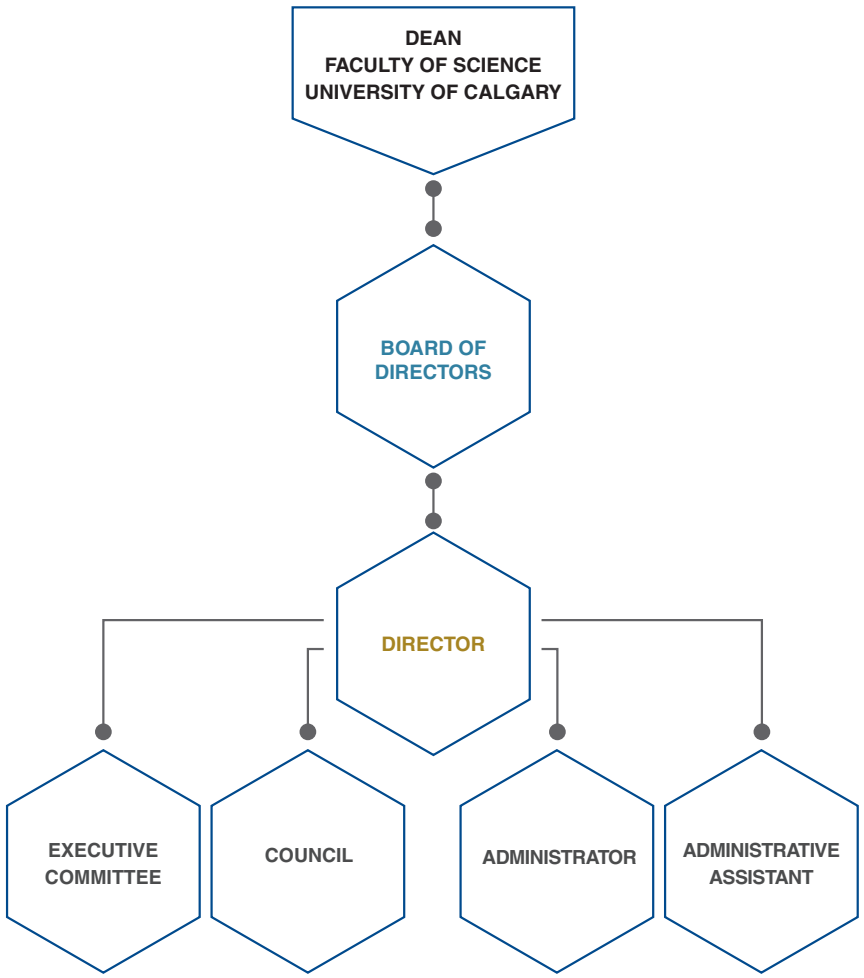
Institute Structure

The Institute is managed on a day-to-day level by the Institute Director and the Institute Administrator. The Director and his research group are additionally supported by an administrative assistant. The Director reports to the Board of Directors and is ex officio a member of this Board. The Board reports to the Dean of Faculty of Science who chairs the Board.

The Director and the Administrator of the Institute work on day-to-day matters of the Institute. The Institute Executive comprises the Director, Deputy Director, Administrator and two faculty members other than the Director and Deputy Director. The Executive meets monthly to discuss and make decisions on executive matters. The Executive receives advice and guidance from the IQIS Council, which comprises all full and affiliate faculty members of the Institute and meets three times annually.

All of the Institute's research, teaching, service and outreach activities are conducted by faculty members and their research groups.

ORGANIZATIONAL CHART



Governance

BOARD OF DIRECTORS

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Dean, Faculty of Science, University of Calgary

PAUL BRUMER
Professor, Department of Chemistry, University of Toronto

JIM HASLETT
Professor, Department of Electrical and Computer Engineering, University of Calgary

SIR PETER KNIGHT
Principal, The Kavli Royal Society International Centre

GREG LUOMA
President, LuomaTech Inc.

BARRY SANDERS
Director, Institute for Quantum Information Science, University of Calgary

BRIAN UNGER
Professor, Department of Computer Science, University of Calgary

ANDREW VALLERAND
Center for Security Science, Defence R&D Canada

EXECUTIVE COMMITTEE

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Associate Professor, Department of Mathematics and Statistics, University of Calgary

PETER HØYER
Associate Professor, Department of Computer Science, University of Calgary

ALEX LVOVSKY
Professor, Department of Physics and Astronomy, University of Calgary

BARRY SANDERS
Director, Institute for Quantum Information Science, University of Calgary

COUNCIL

PAUL BARCLAY
Assistant Professor, Department of Physics and Astronomy, University of Calgary

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Associate Professor, Department of Physics and Astronomy, University of Calgary

GILAD GOUR
Associate Professor, Department of Mathematics and Statistics, University of Calgary

DAVID HOBILL
Associate Professor, Department of Physics and Astronomy, University of Calgary

PETER HØYER
Associate Professor, Department of Computer Science, University of Calgary

ALEX LVOVSKY
Professor, Department of Physics and Astronomy, University of Calgary

DENNIS SALAHUB
Professor, Institute for Biocomplexity and Informatics, University of Calgary

BARRY SANDERS
Director, Institute for Quantum Information Science, University of Calgary

RENATE SCHEIDLER
Professor, Department of Mathematics and Statistics, University of Calgary

CHRISTOPH SIMON
Associate Professor, Department of Physics and Astronomy, University of Calgary

ROBERT THOMPSON
Professor, Department of Physics and Astronomy, University of Calgary

WOLFANG TITTEL
Professor, Department of Physics and Astronomy, University of Calgary

RICHARD ZACH
Professor, Department of Philosophy, University of Calgary

Students

GRADUATE STUDENTS (PHD PROGRAM)

Mark Adcock (completed December 2012 → Independent Consultant)

Hessa Alotaibi

Nathan Babcock

Philip Chan

Jérémie Choquette (completed April 2012 → Analyst, Baker Hughes)

Adam D'Souza

Catalin Dohotaru

Roohollah (Farid) Ghobadi

Mark Girard

Chris Healey

Khabat Heshami

Jeongwan Jin

Behzad Khanaliloo

Mohammad Khazali

Connor Kupchak

Ben Lavoie

Itzel Lucio Martinez

Andrew MacRae (completed November 2012 → Postdoc, University of California, Berkeley)

Hassan Mallahzadeh

Farokh Mivehvar

Varun Narasimhachar

Jibran Rashid (completed July 2012 → Postdoc, University of Lugano)

Erhan Saglamyurek

Zahra Shaterzadeh Yazdi

Neil Sinclair

Michael Skotiniotis (completed June 2012 → Postdoc, Institute for Quantum Optics and Quantum Information, Innsbruck)

Joshua Slater

Borzumehr Toloui Semnani (completed November 2012 → Postdoc, Haverford College)

Michael Underwood (completed December 2012)

Dongsheng Wang

Marcelo Wu

Ehsan Zahedinejad

GRADUATE STUDENTS (MSC PROGRAM)

Khulud Almutairi

Erick Barrios (completed April 2012 → PhD, National and Autonomous University of Mexico)

Kevin Van De Bogart (terminated December 2012)

Travis Brannan

Aveek Chandra

Ran Hee Choi (completed September 2012)

Ish Dhand

Mahdi Ebrahimi Kahou (completed December 2012 → PhD, University of Calgary)

Hamidreza Kaviani (completed December 2012 → PhD, University of Calgary)

Ranjeet Kumar (completed August 2012 → PhD, University of California, San Diego)

Pantita Palittapongarnpim (completed September 2012 → PhD, University of Calgary)

Edouard Pelchat

Adarsh Prasad

Terence Stuart

Ryan Thomas (completed September 2012 → Analyst, CGG Veritas)

Venkata Ramana Raju Valivarthi

Tian Wang

UNDERGRADUATE STUDENTS

Michael Briscoe (NSERC USRA)

Spencer Cameron (PHYS 599)

Deborah Chung (research assistant)

James Clark (PHYS 598)

Stephen Huang (research assistant)

Jeff Maki (NSERC USRA & PHYS 598)

Matthew Mitchell (PHYS 598)

Randy Squires (research assistant & PHYS 598)

Postdoctoral Fellows

Vlad Gheorghiu

Bing He

Morgan Hedges

Patrick Ming-yin Leung (completed September 2012 → Research Engineer, Infotoo International Ltd.)

Neil Lovett

Daniel Oblak

Yang Tan (completed September 2012)

Collin Trail

Yunjiang Wang

Jian Ming Wen (completed April 2012 → Associate Research Scientist, Yale University)

Administration and Support

Arina Esmaeilpour (part-time)

Catherine Barrett

Vladimir Kiselyov

Nancy Jing Lu

Lucia Wang

PUBLICATIONS AND PRESENTATIONS

Refereed Journals

A. Anis and A. I. Lvovsky, "Maximum-likelihood coherent-state quantum process tomography", *New Journal of Physics* **14**(10): 105021 (16 pp.), 19 October 2012.

S. Bray, F. Hoeft, D. S. Hong and A. L. Reiss, "Aberrant functional network recruitment of posterior parietal cortex in Turner syndrome", *Human Brain Mapping*, 19 June 2012 (published on line).

J. Clark, K. Heshami and C. Simon, "Photonic quantum memory in two-level ensembles based on modulating the refractive index in time: equivalence to gradient echo memory", *Physical Review A* **86**(1): 013833 (5 pp.), 23 July 2012.

P. J. Coles, V. Gheorghiu and R. B. Griffiths, "Collisional decoherence of tunneling molecules: a consistent histories treatment", *Physical Review A* **86**(4): 042111 (15 pp.), 11 October 2012.

A. Ferenczi, V. Narasimhachar and N. Lütkenhaus, "Security proof of the unbalanced phase-encoded Bennett-Brassard 1984 protocol", *Physical Review A* **86**(4): 042327 (10 pp.), 19 October 2012.

B. Fortescue and G. Gour, "Reducing the quantum communication cost of quantum secret sharing", *IEEE Transactions on Information Theory* **58**(10): 6659 – 6666, 25 June 2012.

V. Gheorghiu, "Generalized semiquantum secret-sharing schemes", *Physical Review A* **85**(5): 052309 (10 pp.), 15 May 2012.

V. Gheorghiu and G. Gour, "Multipartite entanglement evolution under separable operations", *Physical Review A* **86**(5): 050302 (R) (5 pp.), 7 November 2012.

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M. S. Underwood and D. L. Feder, "Bose-Hubbard model for universal quantum-walk-based computation", *Physical Review A* **85**(5): 052314 (9 pp.), 22 May 2012.

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Conference Proceedings

M. Wu, A. C. Hryciw, B. Khanaliloo, M. R. Freeman, J. P. Davis and P. E. Barclay, "Photonic crystal paddle nanocavities for optomechanical torsion sensing", Proceedings of CLEO: QELS 2012 Fundamental Science (CLEO: 2012), San Jose, United States of America, 6 May 2012 – 11 May 2012.

Invited Conference/Workshop Presentations

(presenter is underlined)

27 Apr 2012, G. Gour, "Local additivity of the minimum entropy output of a quantum channel", North West Functional Analysis Seminar, Banff, Canada, 30 Mar 2012 – 1 Apr 2012.

4 May 2012, V. Gheorghiu and G. Gour, "Quantum entanglement: properties and evolution", The 12th Annual Alberta Colleges Mathematics Conference and North-South Dialogue in Mathematics, Edmonton, Canada, 3 May 2012 – 4 May 2012.

10 May 2012, B. C. Sanders, "Security through quantum communication", 4th International High Speed Intelligent Communication Forum (HSIC 2012), Nanjing, People's Republic of China, 10 May 2012 – 11 May 2012.

10 May 2012, W. Tittel, "How to overcome the distance barrier in quantum communication: quantum repeaters and quantum memory", CLEO: QELS 2012 Fundamental Science (CLEO: 2012), San Jose, United States of America, 6 May 2012 – 11 May 2012.

23 May 2012, A. MacRae, T. Brannan, P. Palittapongarnpim, R. Achal and A. I. Lvovsky, "Single photons generated by atoms", Quantum 2012 – Workshop ad memoriam of Carlo Novero (Quantum 2012), Turin, Italy, 20 May 2012 – 26 May 2012.

28 May 2012, P. E. Barclay, "Nanophotonics and quantum optics in CVD diamond", 95th Canadian Chemistry Conference and Exhibition (CSC 2012), Calgary, Canada, 26 May 2012 – 30 May 2012.

1 Jun 2012, W. Tittel, "Entanglement for QKD", The Greatest Inspiration Surely Is Nonlocality Workshop, Val-d'Illiez, Switzerland, 29 May 2012 – 1 Jun 2012.

3 Jun 2012, G. Gour and S. Friedland, "Closed formula for the relative entropy of entanglement", 2012 Canadian Mathematical Society Summer Meeting, Regina, Canada, 2 Jun 2012 – 4 Jun 2012.

9 Jun 2012, B. C. Sanders, "Universal quantum simulation for fun & profit", Theory Canada 7, Lethbridge, Canada, 7 Jun 2012 – 9 Jun 2012.

4 Jul 2012, A. MacRae, T. Brannan, R. Achal and A. I. Lvovsky, "Tomography of single photons and qubits generated by atoms", Central European Workshop on Quantum Optics, Sinaia, Romania, 2 Jul 2012 – 6 Jul 2012.

23 Jul 2012, T. Brannan, A. MacRae, R. Achal and A. I. Lvovsky, "Towards engineering arbitrary superpositions of collective spin excitations", 21st International Laser Physics Workshop (LPHYS'12), Calgary, Canada, 23 Jul 2012 – 27 Jul 2012.

25 Jul 2012, R. Thomas, C. Kupchak, G. S. Agarwal and A. I. Lvovsky, "Electromagnetically induced transparency with evanescent fields", 21st International Laser Physics Workshop (LPHYS'12), Calgary, Canada, 23 Jul 2012 – 27 Jul 2012.

27 Jul 2012, A. Rubenok, J. A. Slater, P. Chan, I. Lucio Martinez and W. Tittel, "Proof-of-principle demonstration of quantum key distribution immune to detector attacks over deployed optical fiber", 21st International Laser Physics Workshop (LPHYS'12), Calgary, Canada, 23 Jul 2012 – 27 Jul 2012.

2 Aug 2012, N. Sinclair, E. Saglamyurek, H. Mallahzadeh, J. A. Slater, J. Jin, C. Simon, D. Oblak, M. George, R. Ricken, W. Sohler and W. Tittel, "Quantum repeaters using frequency-multiplexed quantum memories", 11th International Conference on Quantum Communication, Measurement and Computing (QCMC 2012), Vienna, Austria, 30 Jul 2012 – 3 Aug 2012.

13 Aug 2012, P. E. Barclay, "Impurities in diamond", Gordon Research Conference on Defects in Semiconductors, Biddeford, United States of America, 12 Aug 2012 – 17 Aug 2012.

16 Aug 2012, T. Brannan, A. MacRae, R. Achal and A. I. Lvovsky, "Tomography of a high-purity narrowband photon from four-wave mixing in atomic vapour", Quantum Communications and Quantum Imaging X (SPIE O&P), San

Diego, United States of America, 15 Aug 2012 – 16 Aug 2012.

27 Aug 2012, E. Saglamyurek, N. Sinclair, H. Mallahzadeh, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, "Quantum memory and entanglement", 11th International Conference on Hole Burning, Single Molecule and Related Spectroscopies: Science and Applications (HBSM 2012), Tuebingen, Germany, 27 Aug 2012 – 30 Aug 2012.

28 Aug 2012, B. C. Sanders, "SU(3) quantum interferometry with single-photon input pulses", International Conference on Quantum Foundation and Technology: Frontier and Future (ICQFT'2012), Dunhuang, People's Republic of China, 25 Aug 2012 – 30 Aug 2012.

29 Aug 2012, A. Rubenok, J. A. Slater, P. Chan, I. Lucio Martinez and W. Tittel, "Proof-of-principle demonstration of QKD immune to detector attacks", Quantum Communication: Secure Information Transmission in the Maritime Environment, Los Angeles, United States of America, 28 Aug 2012 – 30 Aug 2012.

3 Oct 2012, W. Tittel, "Quantum cryptography", Cybersummit 2012, Banff, Canada, 1 Oct 2012 – 3 Oct 2012.

17 Oct 2012, A. MacRae, T. Brannan and A. I. Lvovsky, "Narrowband photon from an atomic source", Frontiers in Optics 2012, Orlando, United States of America, 14 Oct 2012 – 18 Oct 2012.

24 Oct 2012, B. C. Sanders, D.-S. Wang, M. C. de Oliveira and D. W. Berry, "Universal quantum simulation for open-system dynamics", Workshop on Quantum Simulations, Bilbao, Spain, 22 Oct 2012 – 25 Oct 2012.

5 Nov 2012, P. E. Barclay, "Nanoscale silicon optomechanics", Si-EPIC Program Active Photonics Workshop 2012, Vancouver, Canada, 2 Nov 2012 – 5 Nov 2012.

5 Nov 2012, A. I. Lvovsky, "Synthesis, manipulation, measurement and storage of quantum information carried by light" (keynote), Latin American Optics and Photonics (LAOP 2012), São Sebastião, Brazil, 4 Nov 2012 – 8 Nov 2012.

14 Nov 2012, A. Rubenok, J. A. Slater, P. Chan, I. Lucio Martinez and W. Tittel, "Proof-of-principle field test of quantum key distribution immune to detector attacks", CIFAR meeting, Ottawa, Canada, 14 Nov 2012 – 16 Nov 2012.

26 Nov 2012, B. C. Sanders, "Forty-five years of entangled coherent states", International Workshop on Entangled Coherent States, Tokyo, Japan, 26 Nov 2012 – 28 Nov 2012.

Patent

S. Moiseev, A. Kamli and B. C. Sanders, "Fast all-optical switch", assigned serial no. US8264759B2, filed 12 May, 2010, publication date: 11 September 2012.

Student Theses

M. Adcock, "Continuous-variable quantum computation of oracle decision problems" (PhD Thesis), 1 December 2012.

R. H. Choi, "Entanglement sharing protocol via quantum error correcting code" (MSc Thesis), 1 September 2012.

M. Ebrahimi Kahou, "Spatial search via non-linear quantum walk" (MSc Thesis), 1 December 2012.

H. Kaviani, "Quantum storage and retrieval of light by sweeping the atomic frequency" (MSc Thesis), 1 December 2012.

R. Kumar, "Process tomography of photon creation and annihilation operators" (MSc Thesis), 19 July 2012.

A. MacRae, "An atomic source of quantum light" (PhD Thesis), 1 June 2012.

P. Palittapongarnpim, "Characterization of magneto-optical trap for experiments in light-atom interfacing" (MSc Thesis), 1 September 2012.

J. Rashid, "Limits and consequences of nonlocality distillation" (PhD Thesis nominated by the Department of Computer Science for the Governor General's Gold Medal and Chancellor's Graduate Medal Competition 2012), 24 April 2012.

M. Skotiniotis, "Rate of alignment and communication using quantum systems in the absence of a shared frame of reference" (PhD Thesis), 29 June 2012.

R. Thomas, "Observation and characterization of electromagnetically induced transparency using evanescent fields" (MSc Thesis), 1 September 2012.

LINKAGE

Collaboration

IQIS and its members have strong linkage with various external organizations and research networks. Barry Sanders is the principal investigator of the Pacific Institute for the Mathematical Sciences Collaborative Research Group for the Mathematics of Quantum Information, which brings together cognate researchers at the University of Calgary, the University of British Columbia, Simon Fraser University and the University of Washington. Some IQIS Faculty are members of the Canadian Institute for Advanced Research (CIFAR) Quantum Information Processing Program. CryptoWorks21 is the new NSERC Collaborative Research and Training (CREATE) Program for cryptographic training to meet 21st Century threats, and Sanders is on the Management Committee and also serves as Chair of the Professional Skills Working Group. As for new networks, Christoph Simon and Wolfgang Tittel are part of a DARPA network supporting the effort to build a quantum repeater. IQIS has established linkage with Canada's National Institute for Nanotechnology (NINT) in Edmonton through the appointment of Paul Barclay at the University of Calgary and his 50% secondment to NINT. Alex Lvovsky is a member of scientific committee of the Russian Quantum Center.

INTERNATIONAL INSTITUTIONS

Carnegie Mellon University, United States of America
China Southeast University, People's Republic of China
ETH Zürich, Switzerland
Hewlett-Packard Laboratories, United States of America
Huaqiao University, People's Republic of China
Indian Institute of Technology, Kharagpur, India
Jazan University, Saudi Arabia
Kazan Physical-Technical Institute of the Russian Academy of Science, Russia
Leiden University, The Netherlands
Macquarie University, Australia
Massachusetts Institute of Technology, United States of America
National University of Singapore, Singapore
Oklahoma State University, United States of America
Sharif University of Technology, Iran
The Institute for Photonic Sciences, Barcelona, Spain
The National Centre for Mathematics and Physics, KACST, Saudi Arabia
The Russian Quantum Centre, Russia
Università della Svizzera italiana, Switzerland
Universität Paderborn, Germany
Université de Genève, Switzerland
Université de Grenoble, France
Université Paris Diderot, France
Université Paris-Sud 11, France
University of Arizona, United States of America
University of Bristol, United Kingdom
University of California at San Diego, United States of America
University of California at Santa Barbara, United States of America
University of Cambridge, United Kingdom
University of Copenhagen, Demark
University of Illinois at Chicago, United States of America
University of New Mexico, United States of America
University of New South Wales, Australia
University of Queensland, Australia
University of Suwon, South Korea
University of Sydney, Australia

CANADIAN INSTITUTIONS

National Institute for Nanotechnology
Perimeter Institute for Theoretical Physics
Southern Alberta Institute of Technology
Université de Montréal
University of Alberta
University of British Columbia
University of Toronto
University of Waterloo

UNIVERSITY OF CALGARY

Institute for Biocomplexity and Informatics
Institute for Security, Privacy and Information Assurance

Visitors

NAME	INSTITUTION
Alain Aspect	Institut d'Optique
Dominic Berry	Macquarie University
Leslie Bicknell	University of Oregon
Agata Branczyk	University of Toronto
Paul Brumer	University of Toronto
Nicolas Brunner	University of Bristol
Harry Buhrman	University of Amsterdam
Aveek Chandra	McGill University
Aashish Clerk	McGill University
Cécile Crosnier	École Normale Supérieure de Cachan
Aleksey Fedorov	Bauman Moscow State Technical University
Mark Girard	University of Freiburg
Chris Godsil	University of Waterloo
Abhirup Goswami	École Polytechnique
Markus Grassl	National University of Singapore
Hubert de Guise	Lakehead University
Pawel Hawrylak	National Research Council Canada
Amr Helmy	University of Toronto
Amir Kalev	National University of Singapore
Achim Kempf	University of Waterloo
Aeysha Khalique	National University of Science and Technology (NUST)
Jeong San Kim	University of Suwon
Leong Chuan Kwek	University of Singapore
Yury Kurochkin	The Russia Quantum Centre
Angela Lahee	Springer DE
Soojoon Lee	Kyung Hee University
Paul Lett	National Institute of Standards and Technology
Arturo Lezama	Universidad de la República Uruguay
Qing Lin	Huaqiao University
Petr Lisonek	Simon Fraser University
Dylan Mahler	University of Toronto
Peter Marzlin	St. Francis Xavier University
Kamil Michnicki	University of Washington
John Miller	University of Houston
Shahpoor Moradi	Razi University
Andal Narayanan	Raman Research Institute
Tayebeh Naseri	Sharif University of Technology
Marcos Cesar de Oliveira	Universidade Estadual de Campinas
Marella Venkata Panduranga Rao	Indian Institute of Technology, Hyderabad
Andrew Sachrajda	National Research Council Canada
Artur Scherer	Applied Communication Sciences
Neil Turok	Perimeter Institute for Theoretical Physics
Jhon Lozada Vera	Universidade Estadual de Campinas
Fern Watson	Imperial College London
Jiying Zhang	University of Science and Technology of China

TEACHING, TRAINING AND EDUCATION

Quantum Information Graduate Courses

COURSE NAME	INSTRUCTOR	DESCRIPTION
PHYS 615 Advanced Quantum Mechanics I	B. C. Sanders	Basic formalism of the theory and its interpretation, symmetry generators. Scattering theory. Bound states. Changed particles in electric and magnetic fields. Approximation methods.
PHYS 673 Quantum and Nonlinear Optics	A. I. Lvovsky	Fundamentals of quantum and nonlinear optics including atom-photon interactions, coherence, electromagnetically induced transparency, open systems and decoherence, and applications to quantum information technology.

SERVICES AND OUTREACH

Conference Leadership (CHAIR AND CO-CHAIR POSITION ONLY)

MEMBER	COMMITTEE	CONFERENCE/ WORKSHOP	LOCATION	DATES
A. I. Lvovsky	Deputy Chair & Principal Organizer	The Twenty First Annual International Laser Physics Workshop (LPHYS'12)	Calgary, Canada	23 – 27 July 2012
A. I. Lvovsky	Chair, subcommittee, QELS1: Quantum Optics of Atoms, Molecules and Solids	CLEO: Quantum Electronics and Laser Science Conference (QELS) 2013	San Jose, United States of America	9 – 14 June 2013
B. C. Sanders	Co-Chair	2012 Canadian Association of Physicists Congress	Calgary, Canada	10 – 14 June 2012
B. C. Sanders	Chair	The Twenty First Annual International Laser Physics Workshop (LPHYS'12)	Calgary, Canada	23 – 27 July 2012
B. C. Sanders	Program Chair	Quantum Africa 2	Northern Drakensberg, South Africa	3 – 7 Sep 2012
B. C. Sanders	Chair, Program Committee	International Iran Conference on Quantum Information (IICQI 2012)	Tehran, Iran	8 – 12 Sep 2012

Professional Services

NAME	ROLE	JOURNAL/SOCIETY/INSTITUTION
A. I. Lvovsky	Associate Editor	*Optical Express*
A. I. Lvovsky	Member, Scientific Committee	The Russian Quantum Center
A. I. Lvovsky	Advisor	University of Calgary SPIE Student Chapter
B. C. Sanders	Reviewer, Atomic QUantum Technologies (AQUTE) Integrated Project, Information Society and Media, FET–Proactive	European Commission
B. C. Sanders	Member (Canadian representative)	International Council for Quantum Electronics
B. C. Sanders	Member, Editorial Board	*Mathematical Structures in Computer Science*
B. C. Sanders	Member, Advisory Board	NSF CCI Quantum Information Center for Quantum Chemistry
B. C. Sanders	North American Regional Editor (until Aug 2012)	*New Journal of Physics*
B. C. Sanders	Editor (until Sept 2012)	*Optics Communications*
B. C. Sanders	Principal Coordinator, Collaborative Research Group for Mathematics of Quantum Information	Pacific Institute for the Mathematical Sciences
B. C. Sanders	Associate Editor	*Physical Review A*
C. Simon	Guest Editor, Focus Issue on "Quantum Memories"	*New Journal of Physics*

IQIS Public Lecture

Each year the Institute holds a Public Lecture, which has been sponsored each year by Alberta Innovates Technology Futures. In 2012, two hundred participants enjoyed Alain Aspect's wonderful lecture titled ""From Einstein's LichtQuanten to Wheeler's delayed choice: wave particle duality for a single photon". Professor Aspect is an internationally acclaimed physicist at the École Polytechnique in Paris and is a pioneer in the foundations of quantum physics and a recipient of the 2010 Wolf Prize in Physics.

Media Coverage

SOURCE	TITLE OF ARTICLE	LOCATION	DATE
University of Calgary Alumni News	Institute for Quantum Information Science Public Lecture: Alain Aspect	online	1 Apr 2012
New Scientist	Dodge ban on quantum clones to trap Schrödinger's cat: Christoph Simon	online	13 Apr 2012
UToday	A peek into the quantum world of light: Alain Aspect	online	16 Apr 2012
UToday	NSERC CREATE program: Barry Sanders	online	26 Jun 2012
Superconductor Week	U Calgary devises method for microwave pulse storage: Patrick Leung	page 6	30 Jun 2012
Physorg.com	A roll of the dice: Quantum mechanics researchers show that nature is unpredictable: Wolfgang Tittel, Renato Renner	online	9 Jul 2012
Science Codex	A roll of the dice in quantum mechanics is better: Wolfgang Tittel, Renato Renner	online	9 Jul 2012
Science Daily	A roll of the dice: quantum mechanics researchers show that nature is unpredictable: Wolfgang Tittel, Renato Renner	online	9 Jul 2012
ScienceNewsline	A roll of the dice: Wolfgang Tittel, Renato Renner	online	10 Jul 2012
Science2.0	God does play dice with the universe (and the dice are fair): Wolfgang Tittel, Renato Renner	online	11 Jul 2012
UToday	A roll of the dice: Wolfgang Tittel	online	11 Jul 2012
CBC Radio (French)	Interview: La croisere de l'été avec Isabelle Rousseau: Wolfgang Tittel		17 Jul 2012
Physorg.com	Can quantum theory be improved?: Terence Stuart	online	23 Jul 2012
UToday	Laser physicists beam: Alex Lvovsky	online	9 Aug 2012
Science2.0	Quantum entanglement: A third entangled particle?: Christoph Simon	online	17 Dec 2012

Outreach Lectures

14 Jun 2012, P. Høyer, "Quantum algorithmics" (invited), 12th Canadian Summer School on Quantum Information (CSSQI 2012), Waterloo, Canada, 11 Jun 2012 – 16 Jun 2012.

27 Jun 2012, W. Tittel, "Towards repeater-based quantum communication" (invited), JASON Summer Study on Quantum Communication, San Diego, United States of America.

18 Sep 2012, W. Tittel, "Quantum cryptography in the QC2 Lab", presentation to Raytheon, Calgary, Canada.

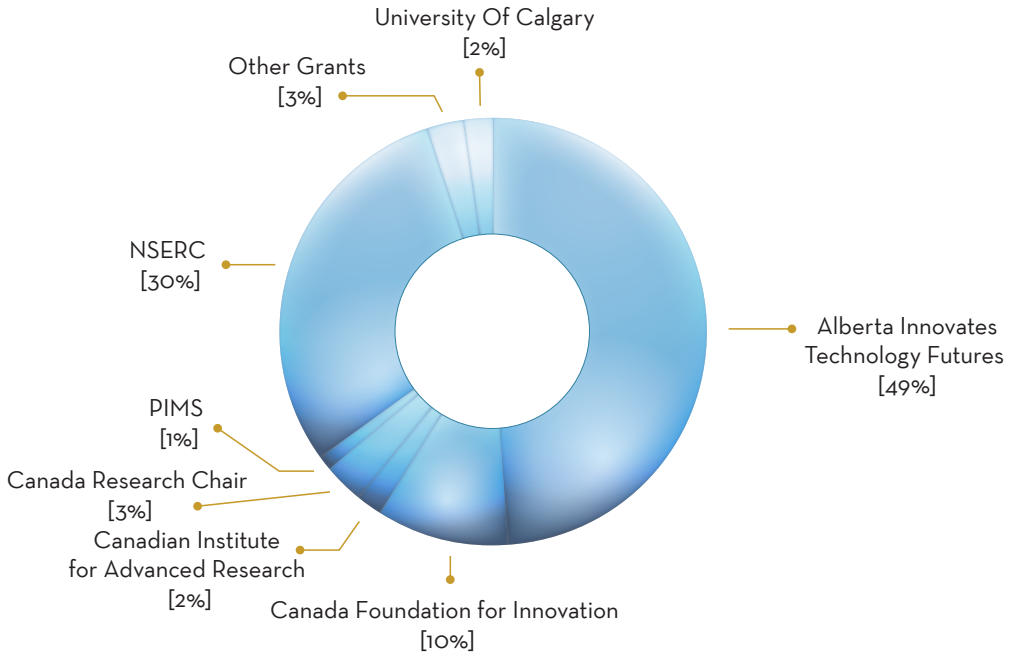
14 Oct 2012, A. I. Lvovsky, "Mysteries and paradoxes of quantum physics", All-Russia Science Festival, Moscow, Russia, 12 Oct 2012 – 14 Oct 2012.

FINANCES

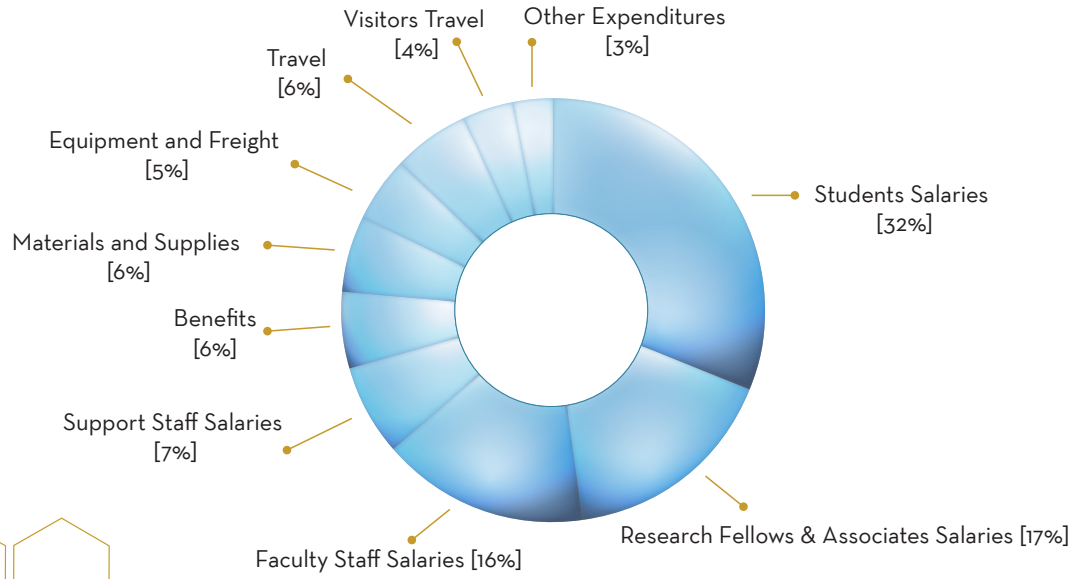
* Information provided is for the period of 9 months from April to December 2012

Research Grants (unaudited)

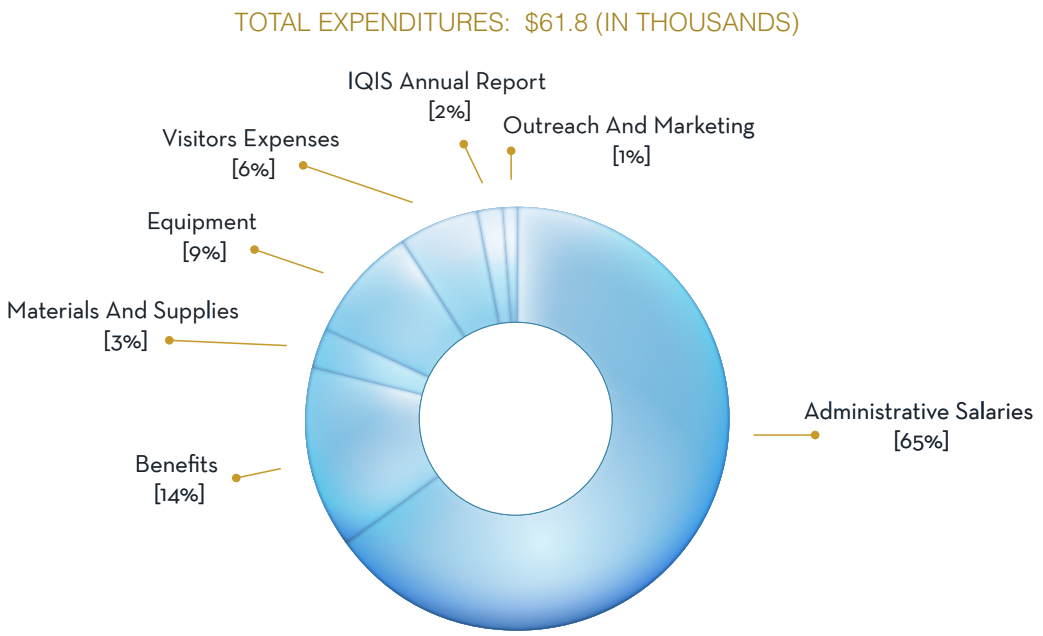
TOTAL REVENUE: $2,890 (IN THOUSANDS)



TOTAL EXPENDITURES: $1,999 (IN THOUSANDS)



Operating Account (unaudited)



PLANS FOR NEXT YEAR

DR. PAUL BARCLAY

In 2013 my group is adding a postdoctoral scholar, up to two graduate students, and hosting three undergraduate summer students (one at NINT, two at UofC). Research efforts will focus on using recently developed optomechanical nanocavities to create sensors for probing properties of quantum systems, and on commencing experiments involving the mechanical manipulation of electronic spins in diamond. The necessary technical infrastructure and research expertise is in place to push forward this first goal.

Development of the diamond experiment is underway, and successful completion of this project will require increased efforts directed toward nanofabrication of diamond based devices plus setup of a single photon confocal microscope. The latter task is expected to make significant progress with the arrival of a recently hired postdoctoral scholar and installation of a custom cryostat scheduled to be delivered in summer 2013.

DR. DAVID FEDER

My group research efforts span topics in atomic, molecular, and optical (AMO) physics, quantum information theory, and condensed matter physics, with particular emphasis on the interfaces between these disciplines. The broad questions to be asked are: how can strong correlations induced in many-body ground states of AMO systems be used to perform quantum algorithms; and how can techniques in quantum information theory be used to probe the properties of condensed matter systems? The work to be conducted in 2013-2014 pursues three main topics along these lines.

One of these topics is: what are the characteristics of quantum many-body states that allow universal measurement-based quantum computation (MBQC)? A promising thread here is that in MBQC the quantum information resides at the surface of a state, much like topologically protected surface modes of symmetry-protected quantum phases. The Haldane phase in condensed matter physics seems to offer various clues here. A second topic is: Is it possible to induce topological insulator states using the strong atom-photon interactions present in cavity quantum electrodynamics?

Preliminary work by a PhD student in my group has recently shown that a single atom in a ring cavity naturally experiences spin-orbit interactions, which is a crucial ingredient in some symmetry-protected states. Future work will test if these states are robust against particle interactions in many-body systems.

Recent calculations by my undergraduate student show that the cavity itself strongly affects van der Waals interactions, which suggests that particle interactions will become very important in these systems. A third topic is: can one devise a real-space renormalization method for interacting quantum gases using graph theory? Preliminary calculations along these lines by my MSc student show that there is a deep connection (and likely a duality in one dimension) between hard-core (infinitely strongly interacting) bosons and non-interacting bosons. If this idea is successful, it should have important applications to understanding the properties of magnetic materials.

DR. GILAD GOUR

My group plan for 2013/14 is to study quantum resource theories (QRTs) and use this knowledge to solve open problems in (1) quantum information, (2) thermodynamics, and (3) quantum optics. Quantum information theory can be viewed as a theory of inter-conversion among different types of resources: classical or quantum, noisy or noiseless, static or dynamics.

Our group will explore inter-conversions between static quantum resources to understand multiparticle entanglement better and to improve the efficiency of important tasks in quantum information. Recently, QRTs have been also used to study thermodynamical systems that are in non-equilibrium states. We will therefore study the resource theory of quantum states out of thermal equilibrium. Finally, we will also explore the resource theory of non-Gaussianity in quantum optics.

DR. ALEX LVOVSKY

In 2013, my group has started a new project on achieving giant optical nonlinear effects in atomic systems. Such nonlinearities can be useful for a variety of purposes, for example, quantum-optical information processing and long distance quantum communications. We will utilize highly nonlinear properties of ultracold atomic ensembles, and, to further enhance these properties, we will contain light in the evanescent field of a tapered optical nanofiber. This project involves several complex components, such as manufacturing optical nanofibers, a specially designed magneto-optical trap, a large number of mutually phase locked diode lasers, etc. We hope to assemble the core of the setup before the end of 2013.

We will continue to pursue our existing experiments involving generation of photon pairs by four-wave mixing in atomic ensembles. Among the goals for 2013/2014 is the preparation and characterization of the single-rail qubit form an atomic source as well as measuring the temporal wavefunction of the heralded photon prepared in this way. In a more distant future we will combine this experiment with quantum-optical memory, which will allow on preparing and measuring arbitrary states of an atomic ensemble.

Finally, we are continuing our line of research on quantum technology of light. Among the goals for 2013 are complete quantum tomography of a two-mode process and the distillation of the Einstein-Podolsky-Rosen state.

DR. BARRY SANDERS

Three decades ago, Richard Feynman motivated quantum computation through his speculation that the nature is not efficiently simulatable on a classical computer but would be efficiently simulatable with a quantum computer. My work has focused on algorithmic quantum simulation, which aims to deliver efficient bounded-error quantum-state generation. This year, in collaboration with Macquarie University, we plan to deliver an efficient circuit-generation algorithm for simulating completely positive maps for few-qubit systems, to initiate a study of quantum-field-simulation quantum algorithms based on manifestly covariant ordered-operator expansions, and to determine limitations to ordered-operator expansions due to finite machine precision.

Quantum simulation is doubly exciting because the problem being solved could be technologically relevant and also the computational resource demands are low compared to other applications of quantum computing hence suggesting that an interesting computational problem could be solved much sooner than expected. Another area of quantum computation has arisen recently: the BosonSampling problem, which is amenable to employing a problem-specific photonic quantum computer that is amenable to current technology. This year my research group will build on non-simultaneous photon-arrival work with co-workers at Singapore's A*STAR and Lakehead University to develop photonic interferometers as matrix-immanant calculators with experimental collaborators at the University of Vienna.

In the area of quantum metrology, which aims to measure parameters like elapsed time or spatial translation with a precision surpassing the semiclassical limit, i.e., shot noise or partition noise, this limit is surpassed by exploiting entanglement. My group has made seminal contributions to adaptive quantum metrology by framing the adaptive algorithm as a decision-tree machine-learning policy and then using reinforcement machine learning to devise "policies" that far outperform previous algorithms and also accommodate real-world effects of noise and loss. Two goals in the coming year are to surpass our previous results by using superior evolutionary algorithms and to apply these techniques beyond quantum metrology to the more general problem of quantum control, which delivers tailored quantum states and transformations with applications to quantum computing and chemical reactions.

A hallmark of my group research has been the proposal of new ways to realize quantum information tasks in the laboratory on a few-year timescale as opposed to decades required for full-scale quantum

computing. In the coming year we will scrutinize opportunities in two different media: microwave pulse control in superconducting artificial atoms that are coupled to an open microwave transmission line (with Université de Sherbrooke and ETH Zürich collaborators) and also the creation of strong nonlinear interactions between two weak optical fields by converting these fields into two strongly interacting species of a Bose-Einstein condensate. The microwave pulse can serve as a quantum bus for mediating quantum information in a large-scale superconducting quantum computer, and the two-species condensate could serve as a few-photon cross-phase modulation element of a photonic interferometer.

Another area of the group's studies of quantum-information implementation has been the multi-year collaboration with the National Institute for Nanotechnology: Wolkow's group creates and controls dangling-bond pairs on the silicon surface. The group's collaborate on characterizing and exploiting these dangling-bond pairs as quantum bits for quantum information processing. In the forthcoming year we will propose a technique for experimental characterization of the tunnelling and decoherence rates for electron transfer between the two nearest dangling bonds and initiate experimental investigation of this system.

My group is exploring electron transfer in a completely different system. Our collaboration with Salahub's University of Calgary Chemistry group has revealed that a water bridge can play an indispensable role for enabling electron transfer between two proteins in a protein complex in contrast to the alternative of through-gap quantum tunnelling. In the coming year we will develop greatly enhanced algorithms for quantum-mechanical and molecular modelling of electron transfer in other protein complexes, and use these new approaches to start tackling the problem of electron transfer in other protein complexes.

The final highlighted goal for the coming year concerns generalized concatenated quantum codes, which we will propose as a systematic technique for constructing good quantum codes from short component codes. This collaboration with Xidian, Singapore National, and Guelph Universities employs the stabilizer formalism and introduces quantum coset codes, which we are using to determine code-distance lower bounds based on component code parameters as well as to exploit the error-correcting capacity of component codes to design good GCQCs efficiently.

DR. CHRISTOPH SIMON

In the area of quantum memories and quantum repeaters, my group is planning to develop new quantum repeater architectures that are well-matched to the current and near-future experimental capabilities of quantum memories based on rare-earth-doped crystals. We will also study the performance requirements on quantum memories for the implementation of heralded entangled photon pair sources. This work will be done in the context of a DARPA project for quantum communication involving Tittel's and my groups. Further on quantum memories, we will study the implementation of photonic quantum memories with ensembles of nitrogen-vacancy centers in collaboration with Paul Barclay here in Calgary and with researchers at HP Labs in California. This approach holds great promise for on-chip integration.

In the area of quantum opto-mechanics, we will study the creation of opto-mechanical entanglement in experimentally relevant regimes that have so far been unaccessible theoretically. We will also study the creation of macroscopic opto-mechanical entanglement through the interaction of mechanical systems with macroscopically entangled states of light, such as those that were recently produced in Lvovsky's lab in a project in which we collaborated on the theory side.

In the area of photon-photon interactions, we will study the interaction between stored photons in atomic ensembles using Rydberg states. We will also investigate the experimental requirements for observing Kerr non-linearities in Bose-Einstein condensates due to atomic collisions.

DR. WOLFGANG TITTEL

My group will focus on two research topics: (1) Quantum Cryptography: we will continue the development of a complete and fully automated measurement-device-independent quantum key distribution system and will also look into possibilities to expand our current point-to-point link into a real-world QKD network; (2) Quantum Repeaters: we will continue developing key primitives for a quantum repeater, including highly multimode quantum memories featuring readout on demand and frequency-multiplexed entangled photon-pair sources. We expect that these developments will lead to the teleportation of photon states into solid-state quantum memory during the coming year.

APPENDICES

Charter

Charter of the Institute for Quantum Information Science at the University of Calgary

Name

1. The name of the organization shall be the Institute for Quantum Information Science at the University of Calgary (hereinafter referred to as "Institute").

Supervising Officer

2. Under the University's policy on Institutes and Centres (ss. 3.4 & 4.6), each institute reports to an appropriate "supervising officer" within the University's administrative structure. The supervising officer of the Institute shall be the Dean of the Faculty of Science.

Approval and Review Bodies

3. The bodies responsible for approving, reviewing, and renewing the Institute under the policy on Institutes and Centres (s. 3.5) are the Dean of the Faculty of Science and the Research Development and Policy Committee (RDPC).

Term of the Institute

4. Under the limited-term provision of the University's policy on Institutes and Centres (s. 4.4), the Institute is established for a seven and half years term ending 30 June 2012. The Institute is eligible for renewal (s. 4.4) upon favourable external review (s. 4.3).

Goals

5. The goals of the Institute shall be:
   a) to establish and maintain leading quantum information science in the areas of quantum algorithms and processing, implications of quantum information on information security and communication complexity, development of physical implementations of quantum information tasks and protocols, and critically evaluate proposals and experimental results in the field;

   b) to educate and train persons with expertise at the frontiers of the allied disciplines of quantum information science;

   c) to bring together top researchers in the world in order to further the development of the field of quantum information science through a focused, multi-disciplinary effort;

   d) to identify promising research areas that will lead to valuable intellectual property and to conduct research in these areas;

   e) to collaborate in complementary research activities in the areas of computer science, engineering, mathematics and experimental and theoretical physics and chemistry.

Targets and Measures of Success

6. At the establishment and/or renewal of an institute, the University's policy on Institutes and Centres (ss. 4.1 & 4.3) requires the setting of targets against which to measure success in adding value.

Schedule of Review

7. Under the terms of the University's Institutes and Centres Policy (ss. 4.1-4.3) and Procedures (ss. 2.4-2.6), the Institute undertakes to be reviewed upon the following schedule during its term:

- at the discretion of the Dean of the Faculty of Science, an internal review after two years of the Institute's limited term;
- as required by the policy on Institutes and Centres, an external review during the final 18 months of the Institute's term.

In addition, the Institute shall submit an annual report on its activities to the Dean of the Faculty of Science.

Institute Board of Directors

8. a) The governing body of the Institute shall be referred to as the "Board of Directors" (hereinafter "Board").

b) Membership of the Board shall comprise:

i. The Institute's "supervising officer" (or designate), who shall Chair the Board and appoint a Vice Chair from among other board members;

ii. At least 4 "members at large," drawn from or nominated by
   - companies whose primary operations are synergistic with quantum information science;
   - agencies that provide funding for quantum information science research in Alberta; and
   - leading members of the quantum information science academic community.

   At least one (1) "member at large" shall be appointed from each of these three categories.

c) The President of the University of Calgary shall appoint "members at large" on the advice of the supervising officer. Terms of appointment, commencing on April 1, shall normally be for three years. This length of appointment may be varied to ensure an appropriate staggering of terms. Members of the Board shall be eligible for re-appointment for consecutive terms of office.

d) The Board shall be responsible for the overall success and governance of the Institute. More particularly, its responsibilities include:

i. approving and/or amending this Charter under the provisions of clause 10 below;
ii. ensuring that relevant University policies are respected (see section 9 below);
iii. appointing a Director for the Institute;
iv. approving the Institute's budget and strategic plans;
v. determining membership categories and requirements for the Institute;
vi. determining the procedures and requirements of general meetings of institute members (with at least one such meeting required annually);
vii. helping to create opportunities for the Institute;
viii. facilitating the periodic reviews and external assessments of the Institute, as required by the University's policy on Institutes and Centres (s. 4.3).

e) The Board shall appoint a Secretary of the Board for a three-year term. The Board can revoke such appointment at any time. The Secretary is not a Board Member and is not eligible to vote.

f) The Board shall meet not less than once in each calendar year, prior to the annual general meeting of Institute members. Special Meetings of the Board shall be convened by the Chair of the Board or upon the written request of at least two (2) members of the Board addressed to the Chair.

i. At least thirty days notice of any meeting shall be given in writing to each member of the Board. Such notice shall specify the time, place and agenda of the meeting;
ii. At any meeting of the Board 50 percent of members, present physically or via teleconference, shall constitute a quorum.

g) The cost for Board members of attending Board meetings (annual and special) will be incurred by the Institute.

Director

9. a) The Director reports to the Board and to the University through the Dean of the Faculty of Science (who, directly or through a designate, chairs the Board).

b) The Director exercises a general superintendence over the operational affairs of the Institute in accordance with the goals of the Institute, and within Board-approved budgets and strategic plans.

c) The duties of the Director shall include, but not be limited to, the following:

i. preparing an annual budget and strategic plan for consideration and approval by the Board;
ii. preparing periodic financial updates for consideration by the Board;
iii. ensuring that all Institute policies and procedures adopted by the Board are made widely known among Institute members and stakeholders, including the broader University of Calgary community;
iv. preparing an annual report on the Institute's affairs, which shall include reporting on measures of success;
v. making any additional submissions or reports, as appropriate or requested, to the Board or the University of Calgary on any matter affecting the Institute;
vi. facilitating the periodic reviews and external assessments of the Institute required by the University's policy on Institutes and Centres (s. 4.3).

Policies and Procedures

10. The Institute will operate in accordance with all applicable University of Calgary policies and procedures.

Amendments

11. Amendments to this Charter shall require approval by the supervising officer and two-thirds of the Board. (The supervising officer may refer proposed amendments to RDPC for its advice.)

IQIS Existing Use of Space

OFFICES

ROOM NUMBER	SIZE (SQUARE METER)
ICT 625A	13
ICT 627	13
ICT 653	13
MS 367	12
MS 436	13
SB 115A	10
SB 115B	10
SB 115C	9
SB 117	12
SB 117A	11
SB 118	5
SB 135	18
SB 303	24
SB 306	54
SB 307	12
SB 312	56
SB 313	12
SB 314	34
SB 315	16
SB 316	32
SB 317	9
SB 318	53
SB 319	19
SB 535	12
SB 318	53
SB 319	19
SB 535	12

LABS

ROOM NUMBER	SIZE (SQUARE METER)
ES 04	248
SB 03A	39
SB 08 & 09	61

IQIS ADDS VALUE TO THE UNIVERSITY OF CALGARY IN THE FOLLOWING WAYS:

Enables a multidisciplinary research through financial and logistical support

Builds a quantum information research community by providing visitor, seminar, and colloquium programs

Assists new faculty members with a rapid transition to becoming productive researchers

Publishes reports and web pages that position the Institute as a leader in quantum information science

Supports recruitment of outstanding faculty, researchers, and graduate students

Sponsors and supports leading conferences held in Calgary

Partners with other quantum information institutes globally

Enhances the University's reputation by delivering outstanding research results

Benefits the wider community by contributing new knowledge in a strategic area

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