
Institute for
Quantum Information Science
at the University of Calgary
ANNUAL REPORT
2011-2012
QUANTUM
FRONTIERS

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

12 POSTDOCTORAL ASSOCIATES / FELLOWS

48 GRADUATE STUDENTS

17 UNDERGRADUATE STUDENTS

40 VISITING RESEARCHERS INCLUDING 5 LONG-TERM VISITING PROFESSORS AND 5 LONG-TERM VISITING STUDENTS

41 PUBLICATIONS IN REFEREED JOURNALS AND CONFERENCE PROCEEDINGS WITH 6 PUBLISHED IN PHYSICAL REVIEW LETTERS AND 1 PUBLISHED IN NATURE PHOTONICS

44 INVITED TALKS AT NATIONAL AND INTERNATIONAL CONFERENCE/ WORKSHOPS INCLUDING 4 PLENARY TALKS AND 2 KEYNOTES

3.2 MILLION DOLLARS CASH INCOME

CONTENTS

DIRECTOR'S REPORT

BARRY SANDERS *(Photo courtesy of the University of Calgary)*

The Institute for Quantum Information Science (IQIS) has had a successful year. The Institute has had three MSc students and one PhD student completing this year. Also the Institute has had high-profile achievements including the Tittel group's result on quantum memory published in Nature and several results in Physical Review Letters discussed in the highlights section of this report. Other important results were published in top journals such as IEEE Transactions on Information Theory. IQIS members have given four plenary presentations, two keynote presentations and thirty-eight invited talks at national and international conferences. The newest IQIS faculty, Paul Barclay, has an operational laboratory and has been obtaining experimental results.

In July 2011, IQIS co-organized a "Quantum-Nano Workshop" in Red Deer. The Calgary side of the organization was undertaken by Paul Barclay and Barry Sanders with the administrative side managed by IQIS Administrator Nancy Jing Lu. The workshop was financially supported by Alberta Innovates - Technology Futures (AITF), and the University of Alberta member of the planning committee was physicist John Davis who is also a National Institute for Nanotechnology (NINT) appointee. The workshop had seventy-one participants including twenty-two Faculty members, three NINT researchers, and two AITF representatives.

The one-day meeting featured three speakers who summarized quantum-nano research activities at the Universities of Alberta and Canada as well as at NINT. Lively poster sessions featured activities by research groups, and there was an open-microphone session at the end of the day, which generated, amongst other results, suggestions for improving the management of graduate scholarships in Alberta. These suggestions were considered by AITF when the organization revised its approach to scholarship management. The workshop helped quantum-nano researchers in Alberta understand the broad spectrum of such activities in the province and is perhaps a first step to future sharing of facilities and collaboration.

In the past year, IQIS has addressed the Faculty of Science challenge to enable all quantum science and technology activities within the Faculty of Science to flourish. Seven Faculty members outside IQIS self-identified as conducting quantum research. Spectroscopists Nasser Moazzen Ahmadi and Rob Thompson are in the Department of Physics & Astronomy. In the Chemistry Department, Peter Kusalik, Dennis Salahub, Yujun Shi, Simon Trudel and Tom Ziegler conduct quantum research in the form of electronic structure calculations, molecular simulations, quantum dots, thin films, and nanomaterials.

After many constructive discussions within IQIS

and separately amongst all quantum researchers, a consensus has built to subsume IQIS into a larger institute comprising the eight IQIS faculty members, the other seven quantum researchers and their groups. The name and logo are still being developed as this report goes to press, but the new institute has a temporary name "Quantum Institute". This new Institute will adopt the governance and management structures of IQIS as well as retain, improve and expand the IQIS database and web pages. AITF will support this new institute at a level of $150,000 per annum for three years with the expectation that the new institute will evolve into a significant provincial force in quantum science and technology and perhaps find synergies with the province's investment in nanotechnology.

The perennial unsolved critical problems continue. The Institute requires quality space for interdisciplinary interactions. Without such space, interactions between groups from different departments remains limited. With the expansion of the Institute to include five chemists, the need for quality interaction space grows ever more important. Furthermore I note that interdisciplinary institutes are essential for the Faculty of Science to have an outstanding research profile commensurate with the University of Calgary's expectations in its "Eyes High" plan, but the Faculty's policy and decision making bodies only have representation from its various Departments with their disciplinary foci and not at all from interdisciplinary institutes. IQIS is not the only Institute to face severe impediments related to the problems of managing personnel, finances, meeting space and contributing directly to Faculty policy.

Interdisciplinarity is growing more important at the University of Calgary and in the academic world at large, and the Faculty of Science should consider how best to nurture interdisciplinarity within and also between the Faculty of Science and other Faculties. That said, I commend the Dean and the Faculty as a whole for its embarkation on fair and transparent procedures for prioritizing research and its wholehearted encouragement of research excellence.

Barry Sanders
Director, IQIS

A MESSAGE FROM THE CHAIR

KEN BARKER

As Chair of the Board of Directors for the University of Calgary's Institute for Quantum Information Science (IQIS), I commend the members of the Institute on their exemplary research and graduate training performance over the past year. The Institute continues to live up to the Faculty of Science's high expectations. Quantum science and technology is a priority area for the Faculty, and the Institute for Quantum Information Science will continue to evolve as an integral part of the Faculty's strategic direction.

In the past year quantum science and technology researchers in the Faculty of Science, including IQIS researchers and seven more from the Departments of Chemistry and Physics & Astronomy, have been working together to develop a bright future for quantum science and technology within the Faculty of Science. This new direction will build on the strengths, and on the renowned brand of IQIS, to create an equally strong but broader-based entity encompassing all quantum researchers within the Faculty. The value of this new quantum institute has been recognized by Alberta Innovates - Technology Futures (AITF), which will finance administrative costs, the visitor program and marketing of this new Institute. During these three years of funding by AITF, the new Institute is expected to establish a formidable presence within Alberta and especially contribute to Alberta innovation as quantum science and technology becomes increasingly important provincially and worldwide.

I also applaud IQIS on its remarkable national and international standing. The Institute is a leader of a Collaborative Research Group within the Pacific Institute for the Mathematical Sciences and leads a project within the National Centre of Excellence for the Mathematics of Information Technology and Complex Systems (MITACS). Members of the Institute are Scholars and Fellows of the Canadian Institute for Advanced Research. The Institute has partnered in a graduate student exchange program with the European Union, specifically with the Canadian side of the collaboration funded by Human Resources and Skills Development Canada. In addition, a new Waterloo-based $1.65m Collaborative Research and Training Experience (CREATE) Program – "Building a Workforce for the Cryptographic Infrastructure of the 21st Century" – includes IQIS as a key partner in this vision.

The University of Calgary's Eyes High vision aims to establish the University of Calgary as one of the top five research universities by its fiftieth anniversary in 2016. IQIS and its successor are key elements of the Faculty of Science's strategy to realize the University's Eyes High vision.

Ken Barker
Chair of the Board of Directors, IQIS

HIGHLIGHTS OF 2011

RESEARCH ACHIEVEMENTS

Of the many research achievements in IQIS during the past year, we emphasize the following. These highlights illustrate both the experimental and the theoretical nature of quantum information science. As well these highlights underscore the interdisciplinarity that exists not only amongst quantum information researchers but also beyond to what is sometimes called quantum information-inspired research.

Christoph Simon and his student Sadegh Raeisi had two important results concerning observability of micro-macro entanglement and also the quantum-to-classical transition. These results were published in Physical Review Letters. The first result, in collaboration with Pavel Sekatski from the University of Geneva, showed that observing macroscopic entanglement in a quantum amplifier requires photon counting with near-single-photon resolution, which is increasingly difficult for large photon numbers.

The second important result from Simon's group, in collaboration with Wolfgang Tittel, discovered a way to circumvent this difficulty by inverting the action of the amplifier. The final measurement can then be performed on a small number of photons while still demonstrating the existence of macroscopic entanglement before the inversion. Physics World and New Scientist reported these results as news stories.

David Feder, together with Ph.D. student Michael Underwood, invented a new kind of quantum walk that is universal for quantum computation. This hybrid of the usual continuous-time and discrete-time quantum walks was dubbed a 'discontinuous quantum walk' because it employs discrete intervals of continuous motion. Using this new approach, it was possible to show that interacting bosons in a two-dimensional lattice, governed by the well-studied Bose-Hubbard model in condensed matter physics, are able to simulate arbitrary quantum algorithms.

Electromagnetically induced transparency is one of the most important enablers for optical quantum information processing in contrast to the closely related phenomenon of Autler-Townes splitting, which is a form of AC Stark shifting. Some experiments report Autler-Townes splitting as electromagnetically induced transparency yet the distinction is critical in judging feasibility for quantum information applications. In collaboration with Dowling's group at Louisiana State University, Sanders showed in a Physical Review Letter how to discern which of the two phenomena has been observed strictly from the experimental data with minimum knowledge of the details of the experiment.

Sanders and his student Hentschel exploited the capabilities of swarm-intelligence machine learning for quantum metrological purposes. Adaptive feedback strategies are hard to find even for ideal cases of noiseless, lossless instruments. Previously Hentschel and Sanders had found a space-efficient procedure for ideal quantum metrology, but the time cost for developing the procedure was exponential in the number of effected phase-shifting operations of the interferometer. In their Physical Review Letter, Hentschel and Sanders described a new heuristic that finds algorithms for noisy, lossy adaptive interferometric phase estimation beyond the standard quantum limit, and this algorithm is efficient with respect to both space and time costs.

Sanders and visiting student Yunjiang Wang from Xidian University, plus collaborators, devised a scheme for iterative decoding of sparse quantum codes that significantly outperforms previous

methods. Belief propagation network techniques were exploited, and the result was published in IEEE Transactions on Information Theory. Wang completed his PhD in China and has returned to the Sanders group as a postdoctoral research associate.

> ...these highlights underscore the interdisciplinarity that exists not only amongst quantum information researchers but also beyond to what is sometimes called quantum information-inspired research.

Gilad Gour and his postdoc Ben Fortecue demonstrated a method to construct perfect quantum secret sharing (QSS) schemes based on imperfect "ramp" secret sharing combined with classical encryption, in which the individual parties' shares are split into quantum and classical components, thereby allowing the former to be of lower dimension than the secret itself. Such schemes can be performed with smaller quantum components and lower overall quantum communication than required for existing methods. This result will be published in IEEE Transactions on Information Theory.

The relative entropy of entanglement is defined in terms of the relative entropy between an entangled state and its closest separable state (CSS). Finding a closed formula for the simple case of two qubits was listed as one of the main 29 open problems in quantum information theory in 2005. Given a multipartite-state on the boundary of the set of separable states, Gour, in collaboration with Shmuel Friedland of the University of Illinois Chicago, found a closed formula for all the entangled state for which this state is a CSS. Quite amazingly, this inverse formula holds for multipartite states in all dimensions.

Wolfgang Tittel and his team implemented a novel quantum key distribution protocol based on two-photon interference that is immune against hacking attacks against single photon detectors. The robustness of the fiber-based implementation, which establishes the possibility for controlled two-photon interference in a real-world environment, along with the enhanced level of security offered by the protocol, confirms quantum key distribution as a realistic technology for safeguarding secrets in transmission. Furthermore, this technological advance removes a remaining obstacle to realizing future applications of quantum communication, such as quantum repeaters and, more generally, quantum networks.

Together with researchers from the Perimeter Institute in Waterloo and ETH Zürich, Tittel and team members have falsified all theories, known or yet-to-be-discovered, that significantly improve the predictions made by quantum mechanics for outcomes of measurements on individual particles. The question as to whether or not the probabilistic nature of quantum mechanics can be alleviated, triggered by Einstein-Podolsky-Rosen in 1935, is central to the foundations of physics as well as quantum information theory. The finding will be published in Physical Review Letters.

In the group of Alex Lvovsky, PhD student Andrew MacRae and his colleagues demonstrated efficient heralded generation of high-purity narrow-bandwidth single photons from a transient collective spin excitation in a hot atomic vapour cell. Employing optical homodyne they reconstruct the density matrix of the generated photon and observe a Wigner function reaching the zero value without correcting for possible inefficiencies. The narrow bandwidth of the photon produced is accompanied by a high generation rate yielding a high spectral brightness. The source is therefore compatible with atomic-based quantum memories as well as other applications in light-atom interfacing. This work paves the way for preparing and measuring arbitrary superposition states of collective atomic excitations.

Paul Barclay and his lab members at the University of Calgary and the National Institute for Nanotechnology (NINT) have had a productive year developing theoretical, fabrication and experimental tools necessary to create nanoscale photonic sensors for quantum systems. PhD student Marcelo Wu and NINT research associate Aaron Hryciw designed a novel type of photonic crystal optomechanical nanocavity optimized for detecting nanoscale sources of torque. Recently, experimental demonstrations of these devices have been obtained in the lab. These devices were fabricated by lab members at NINT and will be used to probe novel nanoscale quantum systems.

AWARDS

International Awards

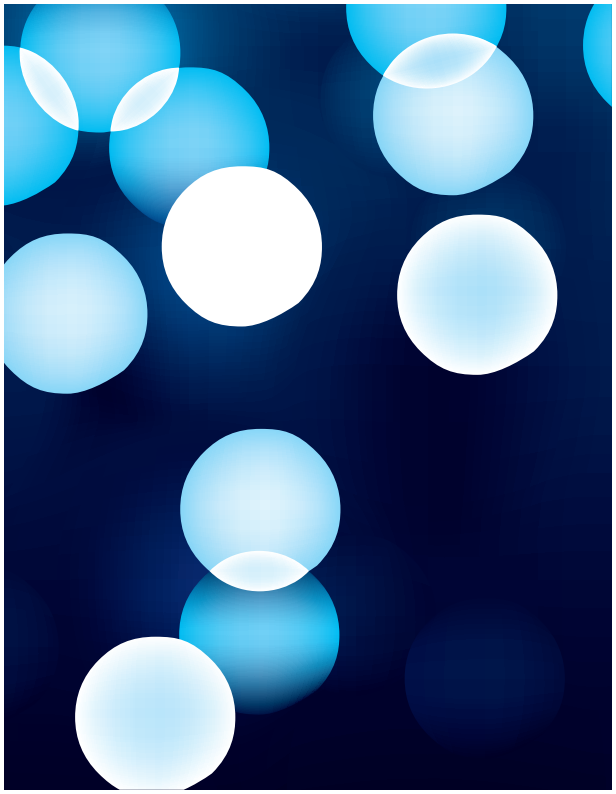
CARLSBERG FOUNDATION AWARD (DENMARK)
Daniel Oblak

CHINESE TOP UNIVERSITY GRADUATE STUDENTS STUDYING ABROAD SCHOLARSHIP (PEOPLE'S REPUBLIC OF CHINA)
Jiying Zhang

KING SAUD UNIVERSITY AWARD (SAUDI ARABIA)
Khulud Almutairi

PAAET AWARD (KUWAIT)
Hessa Alotaibi

THE MEXICAN NATIONAL COUNCIL FOR SCIENCE AND TECHNOLOGY AWARD (MEXICO)
Itzel Lucio Martinez (ended September 2011)



National Awards

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP – DOCTORAL
Connor Kupchak

Joshua Slater

NSERC ALEXANDER GRAHAM BELL CANADA SCHOLARSHIP – MASTERS
Edouard Pelchat

Ryan Thomas (ended August 2011)

NSERC POSTGRADUATE SCHOLARSHIP – DOCTORAL
Philip Chan

Ben Lavoie (ended August 2011)

Andrew MacRae

Michael Underwood (ended August 2011)

NSERC POSTDOCTORAL FELLOWSHIP
Michael Lamont (ended September 2011)

NSERC USRA PROGRAM
Boris Braverman

Alvin Lun

Achal Roshan

PIMS POSTDOCTORAL FELLOWSHIP
Vlad Gheorghiu

Collin Trail

Provincial Awards

ALBERTA INNOVATES GRADUATE STUDENTS SCHOLARSHIP

Adam D'Souza

Connor Kupchak

Ben Lavoie (ended August 2011)

Andrew MacRae

Joshua Slater

Ryan Thomas

Michael Underwood

University of Calgary Awards

DEPARTMENT OF PHYSICS & ASTRONOMY TUITION SCHOLARSHIP

Adam D'Souza

Behzad Khanaliloo

FACULTY OF GRADUATE STUDIES SCHOLARSHIP

Khabat Heshami

PURE AWARD

James Clark

Alexander Penney

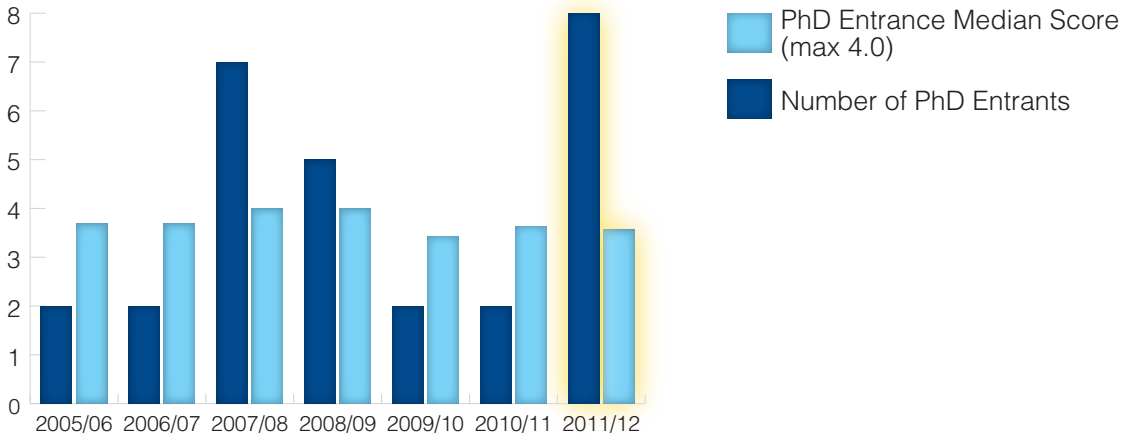
QUEEN ELIZABETH II PHD SCHOLARSHIP

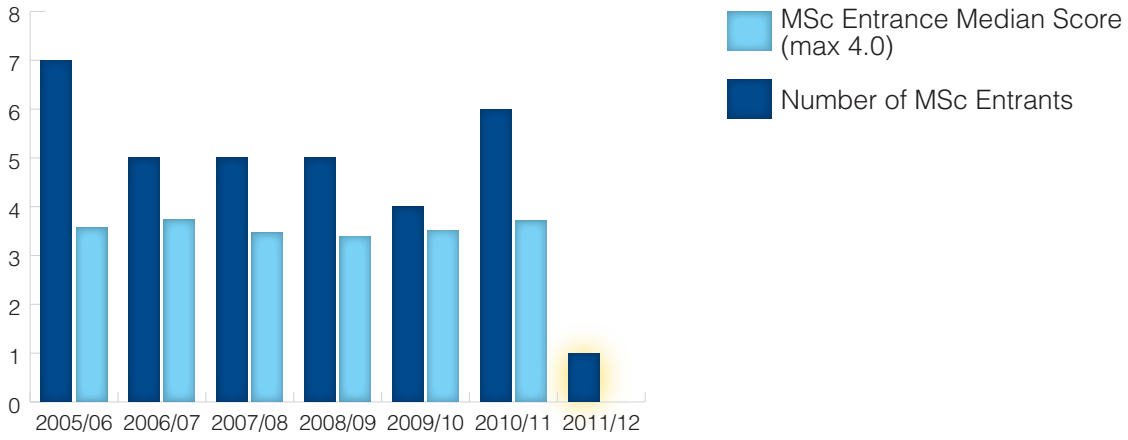
Jibran Rashid

Neil Sinclair

KEY PERFORMANCE INDICATORS

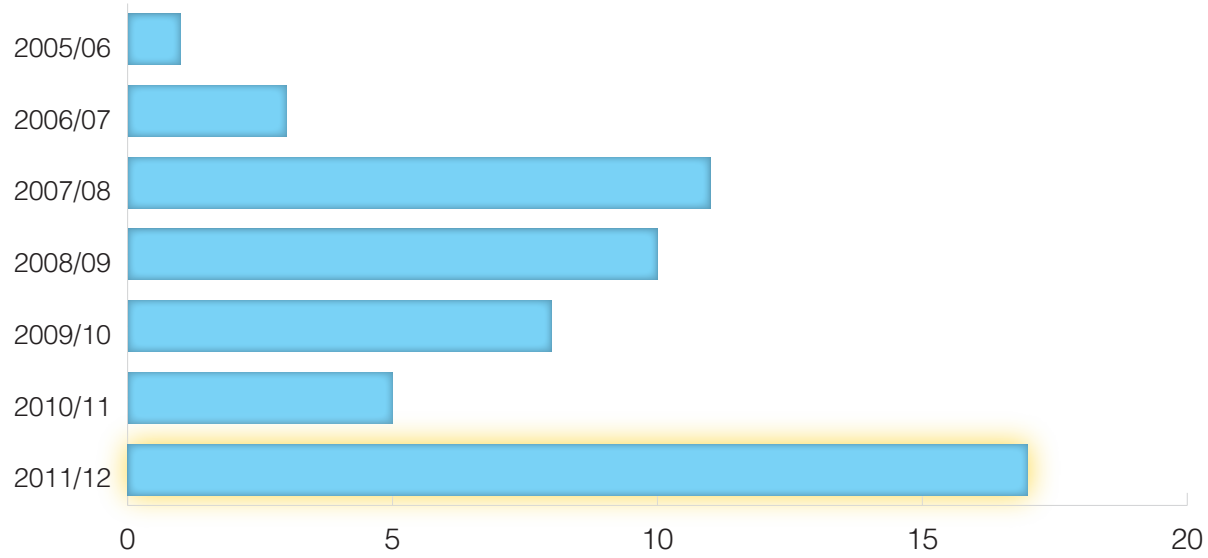
Graduate students enrolment and quality of entrants



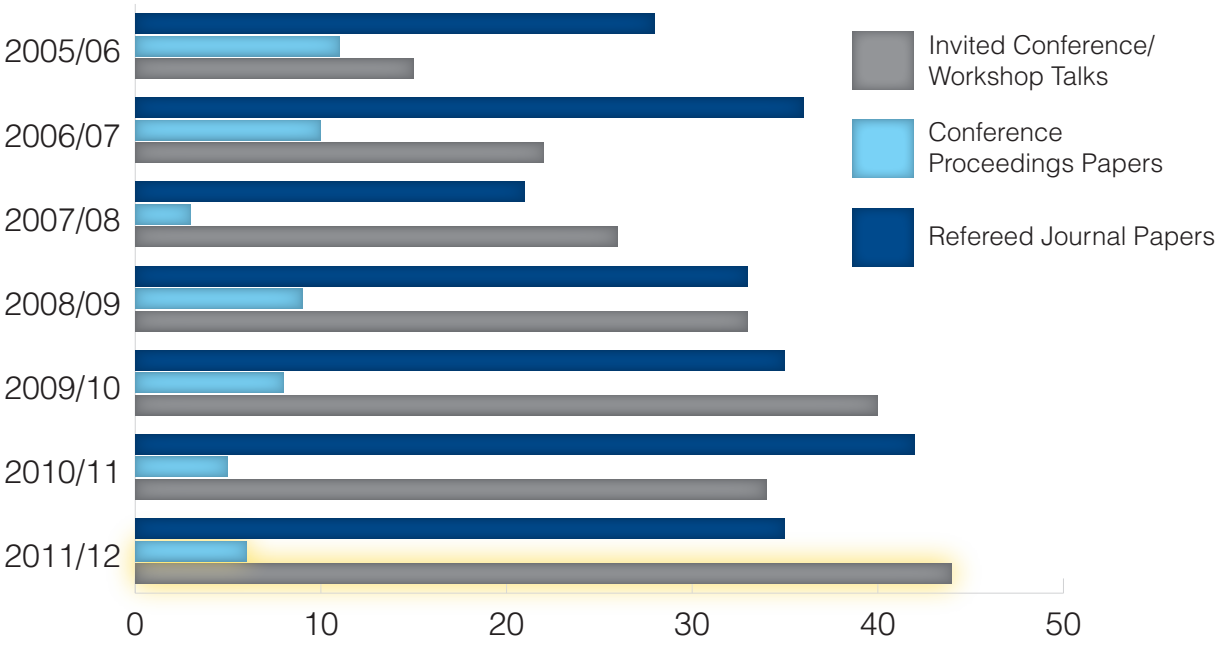


One M.Sc. student registered in the year 2011/12, but for confidentiality reasons the entrance score cannot be published.

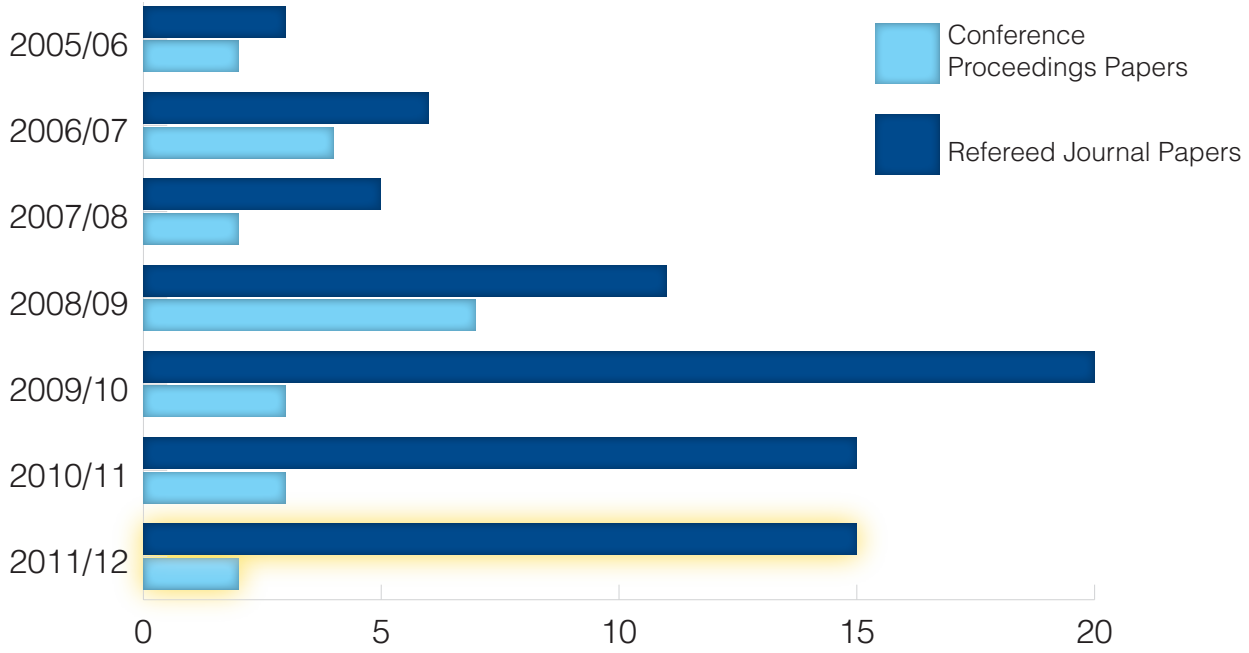
Undergraduate Projects



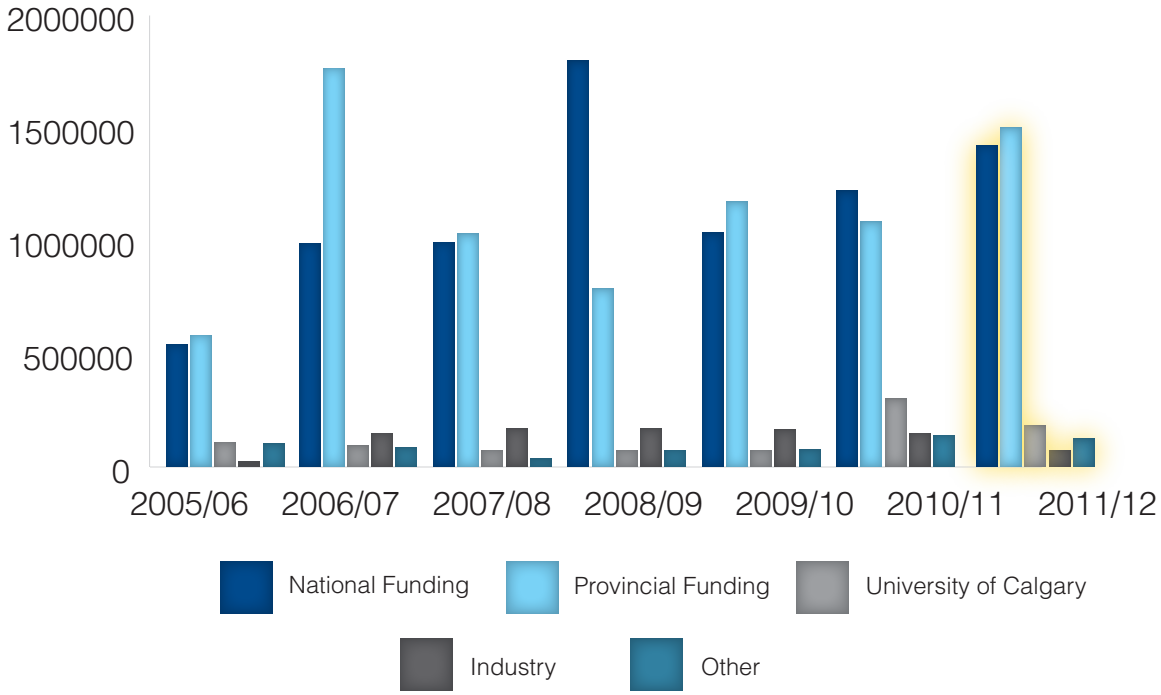
Publications and Presentations



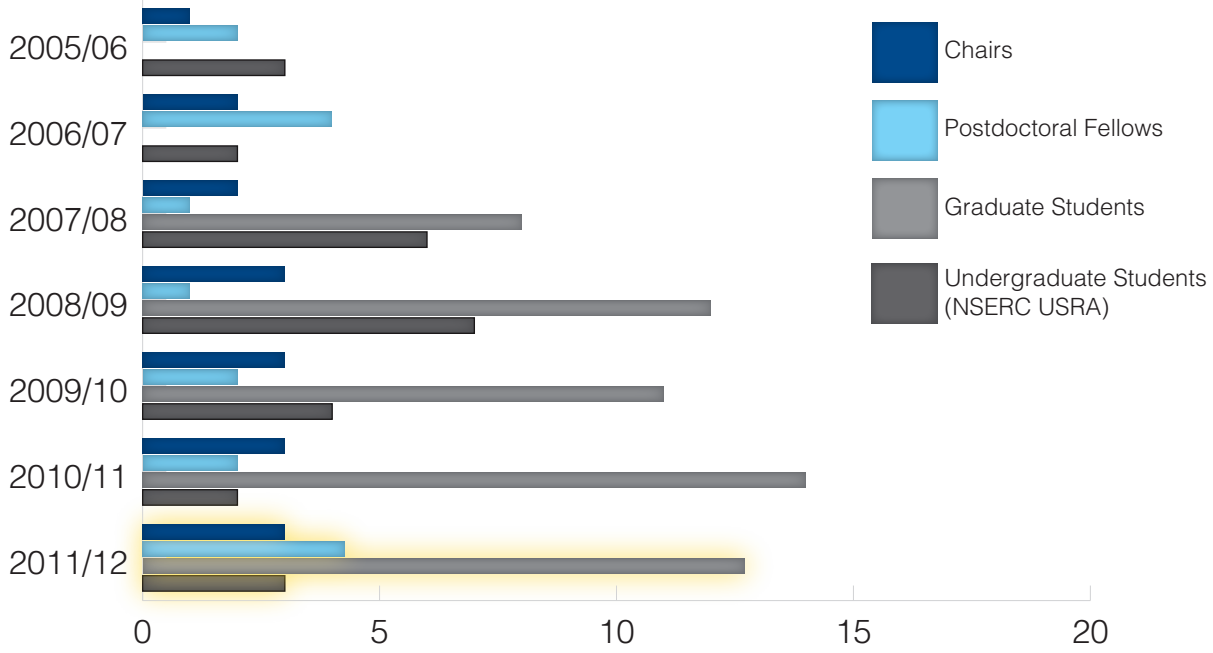
Student Publications



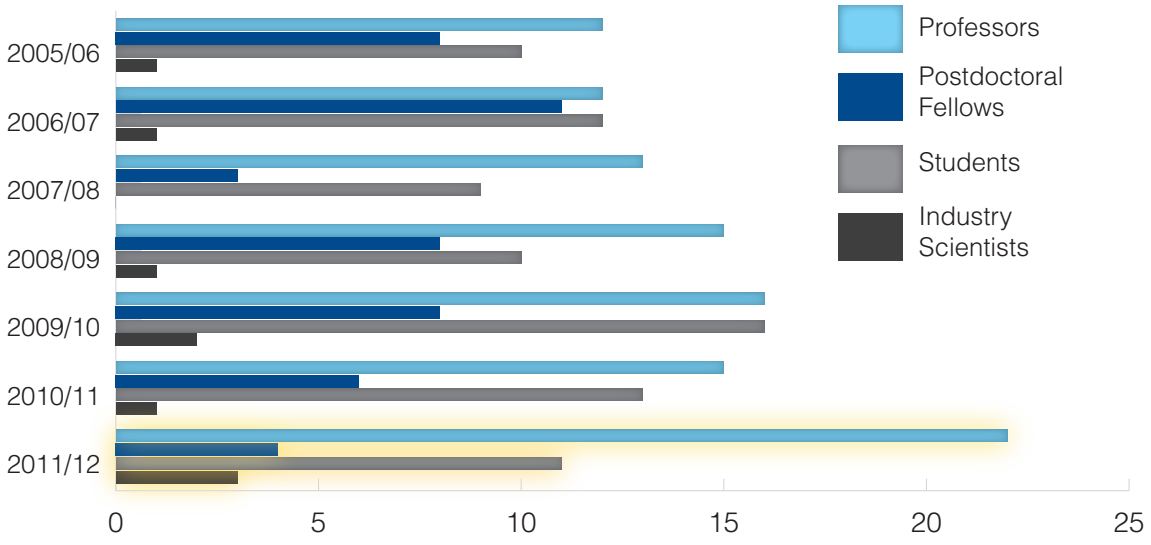
Revenue (unaudited)



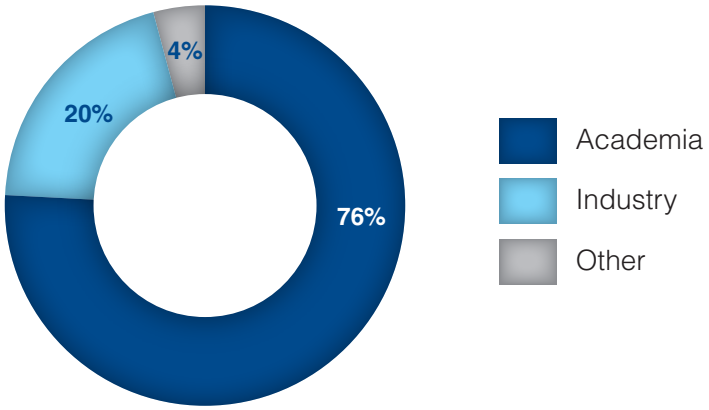
External Awards (Chairs, Fellowships and Scholarships)



Visitors

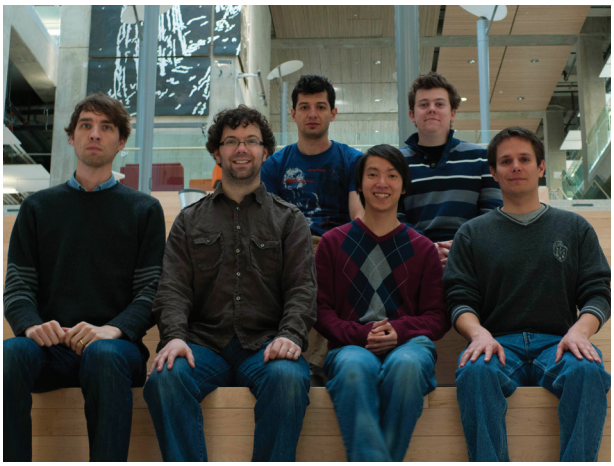


In the Workforce and Academia



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 nano-fabrication methods to engineer the optical proper- ties 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.

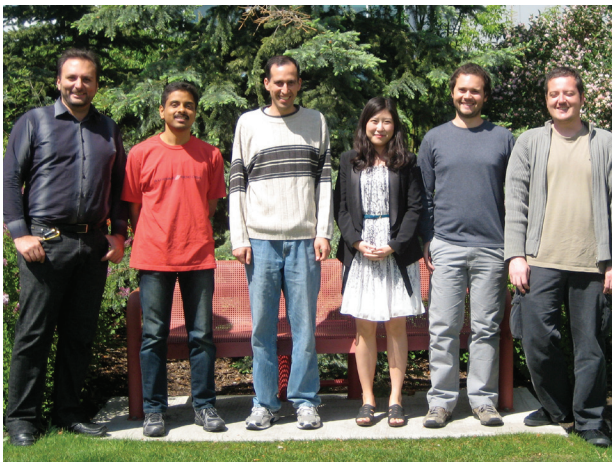
Our current focus involves coupling single quantum emitters, or “artificial atoms” to optical nanocavities. These quantum emitters are formed by impurities in materials such as diamond, whose quantum state is useful for storing information and sensitively probing magnetic fields. This research has applications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

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

PRACTICAL APPROACHES TO QUANTUM COMPUTATION

Dr. David Feder

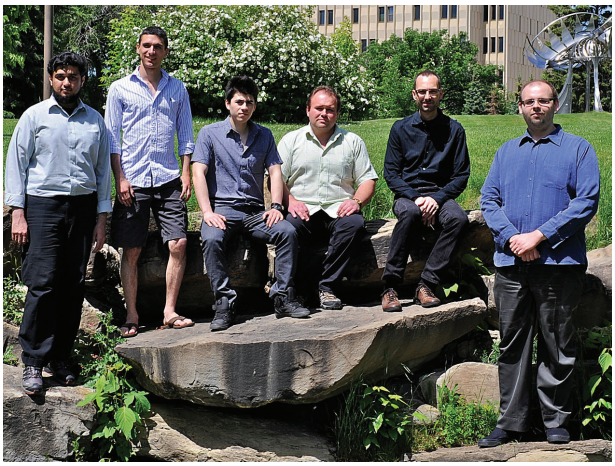
Quantum computers have the potential to solve numerous problems more efficiently than the best-known classical computers, but so far only very small, proof-of-principle quantum computers have been built. The research of our group is focused mainly on understanding how the intrinsic properties of physical 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

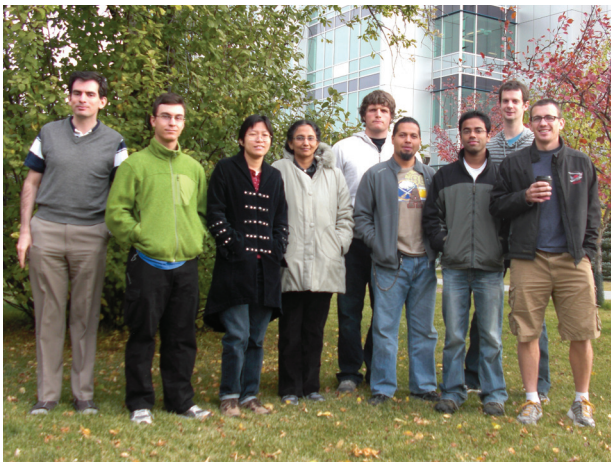
The Quantum Information Group in the Department of Mathematics and Statistics conducts research on the mathematics of quantum information. Theoretical research in quantum information relies on sophisticated mathematical methods, such as algebraic geometry, matrix analysis, group theory and C*-algebras. 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

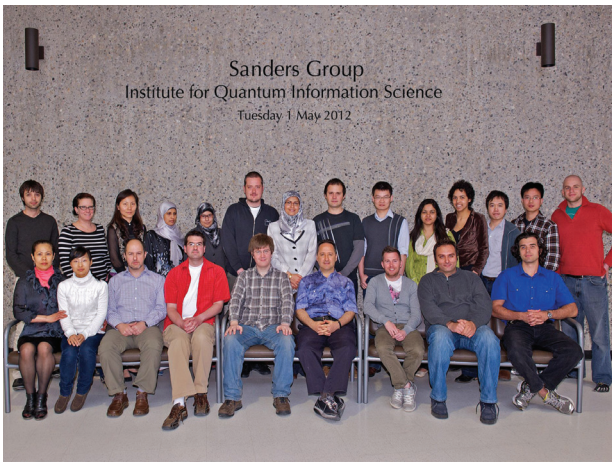
The Quantum Computing Research Group within the Department of Computer Science conducts research in computational aspects of quantum mechanical systems. Quantum computers are in particular interesting because they offer a possibility to achieve computations that cannot be easily achieved on traditional computers. We utilize the potential powers of quantum systems to develop quantum algorithms, quantum communication protocols, and quantum computer simulations of quantum mechanical systems. We conduct work on characterizing these powers and the 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

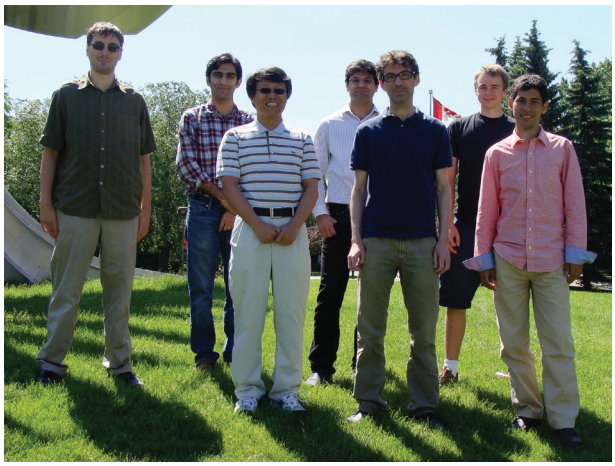
Photons are excellent carriers of quantum information. One can build an entire quantum information processor by means of single-photon sources, detectors, and simple linear optical elements such as mirrors and beam splitters. Our group concentrates on implementing light for the purposes of quantum information 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) quantum 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.

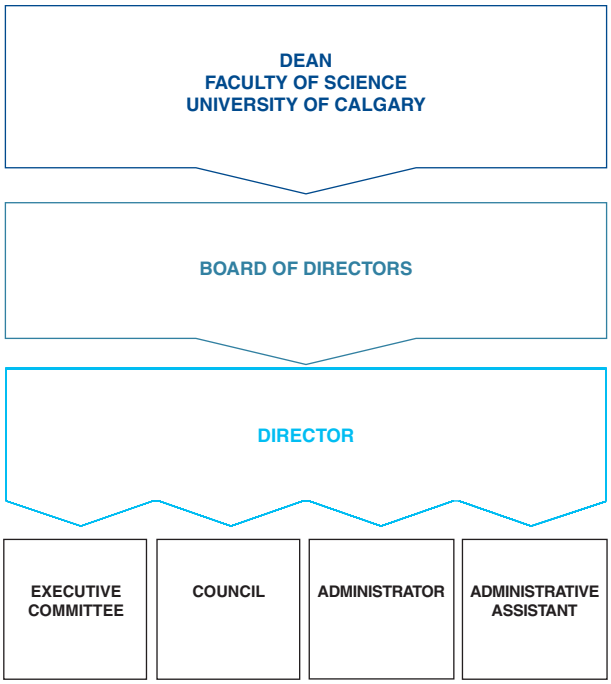
MANAGEMENT & MEMBERSHIP

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

IQIS GOVERNANCE

Board of Directors

KEN BARKER
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

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

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

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

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

Council Committee

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

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

GILAD GOUR
Assistant 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
Associate 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
Associate Professor, Department of Physics and Astronomy, University of Calgary

WOLFANG TITTEL
Associate 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
Hessa Alotaibi
Nathan Babcock
Philip Chan
Jérémie Choquette
Adam D'Souza
Catalin Dohotaru
Roohollah (Farid) Ghobadi
Chris Healey
Alexander Hentschel
(completed May 2011 → Research Scientist, Siemens, Münich)
Khabat Heshami
Jeongwan Jin
Behzad Khanaliloo
Mohammad Khazali
Connor Kupchak
Ben Lavoie
Itzel Lucio Martinez
Andrew MacRae
Hassan Mallahzadeh
Farokh Mivehvar
Varun Narasimhachar
Jibran Rashid
Erhan Saglamyurek
Zahra Shaterzadeh Yazdi
Neil Sinclair
Michael Skotiniotis
Joshua Slater
Borzumehr Toloui Semnani
Michael Underwood
Dongsheng Wang
Marcelo Wu
Ehsan Zahedinejad

Graduate Students (MSc Program)

Khulud Almutairi
Erick Barrios
Kevin Van De Bogart
Travis Brannan
Ran Hee Choi
Chris Healey (completed October 2011→ PhD, University of Calgary)
Mahdi Ebrahimi Kahou
Hamidreza Kaviani
Ranjeet Kumar
Pantita Palittapongarnpim
Edouard Pelchat
Mark Przepiora
Sadegh Raeisi (completed August 2011 → PhD, University of Waterloo)
Allison Rubenok (completed December 2011)
Terence Stuart
Ryan Thomas

Undergraduate Students

Roshan Achal (NSERC USRA)

Aamir Anis (MITACS Globalink)

Boris Braverman (NSERC USRA)

Benjamin Blumer (Research Assistant)

Spencer Cameron (PHYS 599)

James Clark (PHYS 598 & PURE Award)

Chris Dascollas (Research Assistant)

Adam Green (Research Assistant)

Rex Leniczek (Research Assistant)

Chris Luciuk (Research Assistant)

Alvin Lun (NSERC USRA)

Matthew Mitchell (PHYS 598 & Research Assistant)

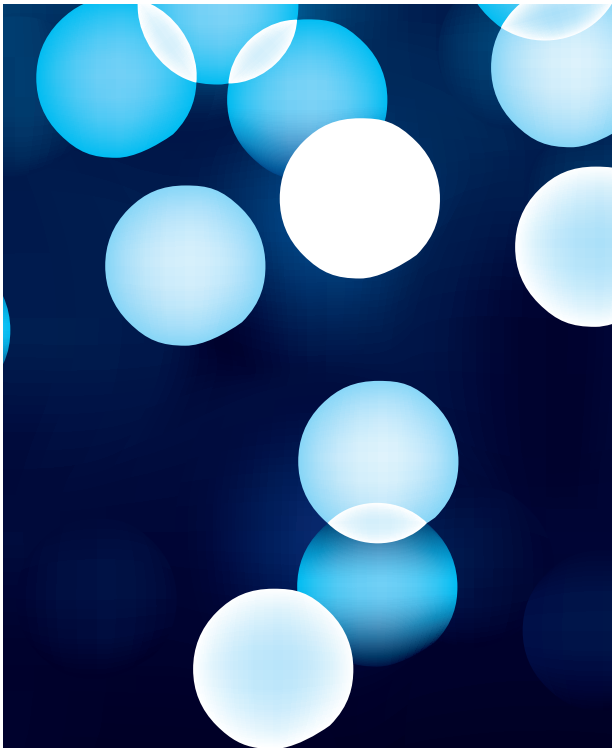
Alex Penney (PURE Award)

Martí Perarnau Llobet
(Research Assistant)

Randy Squires (PHYS 598)

Sweta (Research Assistant)

Alex Tetarenko (PHYS 599)



POSTDOCTORAL FELLOWS

Ben Fortescue (completed August 2011
→ Postdoc, Southern Illinois University)

Vlad Gheorghiu

Jeong San Kim (completed August 2011
→ Assistant Professor, Suwon University)

Michael Lamont (resigned September 2011
→ Postdoc, Cornell University)

Patrick Ming-yin Leung

Neil Lovett

Xiaofan Mo (completed April 2011→ Research
Scientist, China Academy of Space Technology)

Daniel Oblak

Yang Tan

Collin Trail

Yunjiang Wang

Jian Ming Wen

ADMINISTRATION AND SUPPORT

Catherine Kosior (part-time)

Vladimir Kiselyov

Nancy Jing Lu

Jibran Rashid (part-time)

Lucia Wang

PUBLICATIONS AND PRESENTATIONS

REFEREED JOURNALS

K. Almutairi, R. Tanas and Z. Ficek, "Generating two-photon entangled states in a driven two-atom system", *Physical Review A* **84**(1): 013831 (12 pp.), 27 July 2011.

P. M. Anisimov, J. P. Dowling and B. C. Sanders, "Objectively discerning Autler-Townes splitting from electromagnetically induced transparency", *Physical Review Letters* **107**(16): 163604 (4 pp.), 12 October 2011.

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G. Berlin, G. Brassard, F. Bussières, N. Godbout, J. A. Slater and W. Tittel, "Experimental loss-tolerant quantum coin flipping", *Nature Communications* **2**: 561 (7 pp.), 29 November 2011.

D. W. Berry and A. I. Lvovsky, "Preservation of loss in linear-optical processing", *Physical Review A* **84**(4): 042304 (7 pp.), 4 October 2011.

B. A. Blumer, M. S. Underwood and D. L. Feder, "Single-qubit unitary gates by graph scattering", *Physical Review A* **84**(6): 062302 (7 pp.), 5 December 2011.

N. Brunner, E. S. Polzik and C. Simon, "Heralded amplification for precision measurements with spin ensembles", *Physical Review A* **84**(4): 041804(R) (3 pp.), 17 October 2011.

Z. Chen, D. Liu, Y. Zhang, J.-M. Wen, S. Zhu and M. Xiao, "Fractional second-harmonic talbot effect", *Optics Letters* **37**(4): 689 – 691, 14 February 2012.

A. de la Lande, N. S. Babcock, J. Řezáč, B. Lévy, B. C. Sanders and D. R. Salahub, "Quantum effects in biological electron transfer", *Physical Chemistry Chemical Physics* **14**(17): 5902 – 5918, 20 March 2012.

A. G. D'Souza and D. L. Feder, "Strategies for measurement-based quantum computation with cluster states transformed by stochastic local operations and classical communication", *Physical Review A* **84**(4): 042301 (14 pp.), 3 October 2011.

A. Faraon, P. E. Barclay, C. Santori, K.-M. C. Fu and R. G. Beausoleil, "Resonant enhancement of the zero-phonon emission from a color center in a diamond cavity", *Nature Photonics* **5**: 301 – 305, 24 April 2011.

D. L. Feder, "Maximally entangled gapped ground state of lattice fermions", *Physical Review A* **85**(1): 012312 (8 pp.), 12 January 2012.

S. Friedland and G. Gour, "Closed formula for the relative entropy of entanglement in all dimensions", *Journal of Mathematical Physics* **52**(5): 052201 (13 pp.), 20 May 2011.

S. Friedland, G. Gour and A. Roy, "Local extrema of entropy functions under tensor products", *Quantum Information and Computation* **11**(11-12): 1028 – 1044, 1 November 2011.

K.-M. C. Fu, P. E. Barclay, C. Santori, A. Faraon and R. G. Beausoleil, "Low-temperature tapered-fiber probing of diamond NV ensembles coupled to GaP microcavities", *New Journal of Physics* **13**(5): 055023, 31 May 2011.

R. Ghobadi, A. R. Bahrampour and C. Simon, "Optomechanical entanglement in the presence of laser phase noise", *Physical Review A* **84**(6): 063827 (5 pp.), 12 December 2011.

R. Ghobadi, A. R. Bahrampour and C. Simon, "Quantum optomechanics in the bistable regime", *Physical Review A* **84**(3): 033846 (7 pp.), 22 September 2011.

G. Gour and N. R. Wallach, "Necessary and sufficient conditions for local manipulation of multipartite pure quantum states", *New Journal of Physics* **13**(7): 073013 (28 pp.), 11 July 2011.

B. He, Q. Lin and C. Simon, "Cross-Kerr nonlinearity between continuous-mode coherent states and single photons", *Physical Review A* **83**(5): 053826 (8 pp.), 18 May 2011.

B. He and A. Scherer, "Continuous-mode effects and photon-photon phase gate performance", *Physical Review A* **85**(3): 033814 (4 pp.), 16 March 2012.

A. Hentschel and B. C. Sanders, "An efficient algorithm for optimizing adaptive quantum metrology processes", *Physical Review Letters* **107**(23): 233601 (4 pp.), 30 November 2011.

J. S. Kim and B. C. Sanders, "Unified entropy, entanglement measures and monogamy of multi-party entanglement", *Journal of Physics A: Mathematical and Theoretical* **44**(29): 295303 (14 pp.), 20 June 2011.

X. F. Mo, I. Lucio Martinez, P. Chan, C. Healey, S. Hosier and W. Tittel, "Time-cost analysis of a quantum key distribution system clocked at 100 MHz", *Optics Express* **19**(18): 17729 – 17737, 25 August 2011.

S. A. Moiseev and W. Tittel, "Optical quantum memory with generalized time-reversible atom-light interaction", *New Journal of Physics* **13**(6): 063035 (13 pp.), 19 June 2011.

J. O. Orwa, K. Ganesan, J. Newnham, C. Santori, P. E. Barclay, K.-M. C. Fu, R. G. Beausoleil, I. Aharonovich, B. A. Fairchild, P. Olivero, A. D. Greentree and S. Prawer, "An upper limit on the lateral vacancy diffusion length in diamond", *Diamond and Related Materials* **24**: 6 – 10, 11 February 2012.

S. Raeisi, P. Sekatski and C. Simon, "Coarse graining makes it hard to see micro-macro entanglement", *Physical Review Letters* **107**(25): 250401 (5 pp.), 16 December 2011.

S. Raeisi, W. Tittel and C. Simon, "Proposal for inverting the quantum cloning of photons", *Physical Review Letters* **108**(12): 120404 (5 pp.), 22 March 2012.

A. Rispe, B. He and C. Simon, "Photon-photon gates in Bose-Einstein condensates", *Physical Review Letters* **107**(4): 043601 (4 pp.), 18 July 2011.

E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, "Conditional detection of pure quantum states of light after storage in a Tm-doped waveguide", *Physical Review Letters* **108**(8): 083602 (5 pp.), 22 February 2012.

C. Simon and E. S. Polzik, "Fock-state view of weak-value measurements and implementation with photons and atomic ensembles", *Physical Review A* **83**(4): 040101(R) (4 pp.), 25 April 2011.

B. Toloui, G. Gour and B. C. Sanders, "Constructing monotones for quantum phase references in totally dephasing channels", *Physical Review A* **84**(2): 022322 (8 pp.), 17 August 2011.

Y. J. Wang, B. C. Sanders, B.-M. Bai and X.-M. Wang, "Enhanced feedback iterative decoding of sparse quantum codes", *IEEE Transactions on Information Theory* **58**(2): 1231 – 1241, 6 February 2012.

N. Wiebe, D. W. Berry, P. Høyer and B. C. Sanders, "Simulating quantum dynamics on a quantum computer",*Journal of Physics A: Mathematical and General* **44**(44): 445308 (20 pp.), 18 October 2011.

N. Wiebe and N. S. Babcock, "Improved error-scaling for adiabatic quantum evolutions", *New Journal of Physics* **14**(1): 013024 (15 pp.), 16 January 2012.

P. Xue and B. C. Sanders, "Two quantum walkers sharing coins", *Physical Review A* **85**(2): 022307 (8 pp.), 6 February 2012.

CONFERENCE PROCEEDINGS

G. Brassard, P. Høyer, K. Kalach, M. Kaplan, S. Laplante and L. Salvail, "Merkle puzzles in a quantum world", Lecture Notes in Computer Science **6841**, Proceedings of 31st Annual International Conference on Cryptology (CRYPTO 2011), Santa Babara, United States of America, 14 Aug 2011 – 18 Aug 2011, Published by Springer: 391 – 410, 14 August 2011.

B. Lavoie, P. M. Leung and B. C. Sanders, "Waveguide characteristics for arbitrary permittivity and permeability including for metamaterials", Proceedings of SPIE Optics & Photonics 2011 – Metamaterials: Fundamentals and Applications IV, SPIE **8093**, San Diego, United States of America, 21 Aug 2011 – 25 Aug 2011, Published by SPIE Publications, Bellingham, United States of America: 80931T (6 pp.), 1 September 2011.

P. M. Leung and B. C. Sanders, "Electromagnetically controlled storage and retrieval for pulses propagating through a line of atoms", Proceedings of Advances in Photonics of Quantum Computing, Memory, and Communication V, SPIE **8272**, San

Francisco, United States of America, 21 Jan 2012 – 26 Jan 2012, Published by SPIE Publications, Bellingham, United States of America, 16 February 2012.

M. Lobino, S. Rahimi-Keshari, D. Korystov, C. Kupchak, E. Figueroa, A. Scherer, B. C. Sanders and A. I. Lvovsky, "Quantum-optical process tomography using coherent states", Proceedings of 10th International Conference on Quantum Communication, Measurement and Computation (QCMC2010), Brisbane, Australia, 19 Jul 2010 – 23 Jul 2010, Published by American Physical Society (APS), College Park, United States of America: 197 – 206, 22 November 2011,

B. C. Sanders, "Quantum optics in superconducting circuits", Proceedings of The 4th International Workshop on Theoretical and Computational Nano-Photonics (Tacona - Photonics 2011), AIP Conference Proceedings **1398**, Bad Honnef, Germany, 26 Oct 2011 – 28 Oct 2011, Published by American Institute of Physics Inc., Melville, United States of America: 46 – 49, 4 October 2011.

P. Xue, Z. Ficek and B. C. Sanders, "Two coupled Jaynes-Cummings cells", Proceedings of Society of Photo-Optical Instrumentation Engineers: Optics and Photonics 2011, SPIE **8163**, San Diego, United States of America, 21 Aug 2011 – 25 Aug 2011, Published by SPIE Publications, Bellingham, United States of America: 81630Q (7 pp.), 6 September 2011.

BOOK CHAPTERS

P. Chan, I. Lucio Martinez, X. F. Mo and W. Tittel, "Quantum key distribution", section in book: *Femtosecond-Scale Optics*, **Chapter 13**, A. V. Andreev, ed., Published by InTech, 2011.

B. C. Sanders, "Quantum cryptography for information-theoretic security", section in book: *Technological Innovations in Sensing and Detection of Chemical, Biological, Radiological, Nuclear Threats and Ecological Terrorism*, 335 – 343, A. Vaseashta, E. Braman and P. Susmann, eds., Published by Springer, 2012. (Part of Nato's Science for Peace and Security Series)

INVITED CONFERENCE/ WORKSHOP PRESENTATIONS

(PRESENTER IS UNDERLINED)

2 May 2011, B. C. Sanders, "Quantum process tomography with coherent states" (plenary), 12th International Conference on Squeezed States and Uncertainty Relations (ICSSUR), Foz do Iguaçu, Brazil, 2 May 2011 – 6 May 2011.

9 May 2011, B. C. Sanders, "Nonlinear quantum optics in superconducting circuit quantum electrodynamic systems", Quantum Technology International Conference 2011, Deutsches Museum, München, Germany, 9 – 10 May 2011.

19 May 2011, C. Simon, "Quantum repeaters", Canadian Institute for Advanced Research (CIFAR) Meeting, Mt. Tremblant, Canada, 18 May 2011 – 21 May 2011.

20 May 2011, C. Simon, "Photonic quantum information processing", Information Photonics 2011 (IP 2011), Ottawa, Canada, 18 May 2011 – 20 May 2011.

25 May 2011, A. I. Lvovsky, "The Russian Quantum Centre and its planned research", Skolkovo Scientific Conference, St. Petersburg, Russia, 24 May 2011 – 25 May 2011.

26 May 2011, A. I. Lvovsky, "Describing quantum optical 'black boxes'", The Seventh Seminar Dedicated to the Memory of D. N. Klyshko, Moscow, Russia, 25 May 2011 – 27 May 2011.

26 May 2011, B. C. Sanders, "Empirically discerning Autler-Townes splitting from electromagnetically induced transparency", The 5th Asia-Pacific Workshop on Quantum Information Science: in conjunction with the Festschrift in honour of Vladimir Korepin (APWQIS), Singapore, 25 May 2011 – 28 May 2011.

31 May 2011, P. E. Barclay, "Talking to spins with photons: diamond nanophotonics", Canadian Institute for Advanced Research (CIFAR) Nanoelectronics Meeting, Mt. Tremblant, Canada, 31 May 2011 – 31 May 2011.

2 Jun 2011, D. W. Berry and A. I. Lvovsky, "Quantifying optical losses", 18th Central European Workshop on Quantum Optics, Madrid, Spain, 30 May 2011 – 3 Jun 2011.

7 Jun 2011, D. W. Berry and A. I. Lvovsky, “On quantum efficiencies of optical states”, 4th International Conference on Quantum Information (ICQI), Ottawa, Canada, 5 Jun 2011 – 8 Jun 2011.

7 Jun 2011, B. C. Sanders, “Electromagnetically induced transparency in superconducting circuits”, 4th International Conference on Quantum Information (ICQI), Ottawa, Canada, 5 Jun 2011 – 8 Jun 2011.

7 Jun 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, “Broadband waveguide quantum memory for entangled photons”, 4th International Conference on Quantum Information (ICQI), Ottawa, Canada, 5 Jun 2011 – 8 Jun 2011.

13 Jun 2011, A. I. Lvovsky, “Three ways to characterize a quantum-optical black box”, Foundations of Probability and Physics 6, Växjö, Sweden, 13 Jun 2011 – 16 Jun 2011.

30 Jun 2011, B. C. Sanders, “Whither quantum computing?”, 36th International Nathiagali Summer College on Physics & Contemporary Needs (INSC), Islamabad, Pakistan, 27 Jun 2011 – 8 Jul 2011.

1 Jul 2011, B. C. Sanders, “Seeing through electromagnetically induced transparency”, 36th International Nathiagali Summer College on Physics & Contemporary Needs (INSC), Islamabad, Pakistan, 27 Jun 2011 – 8 Jul 2011.

2 Jul 2011, B. C. Sanders, “Swarm learning for precise quantum measurements”, 36th International Nathiagali Summer College on Physics & Contemporary Needs (INSC), Islamabad, Pakistan, 27 Jun 2011 – 8 Jul 2011.

6 Jul 2011, W. Tittel, “Quantum-Nano highlights at the University of Calgary”, Alberta Quantum and Nano Optics Workshop 2011, Red Deer, Canada.

11 Jul 2011, D. W. Berry and A. I. Lvovsky, “Quantum efficiency of an optical state: a general theory”, 20th International Laser Physics Workshop (LPHYS’11), Sarajevo, Bosnia and Herzegovina, 11 Jul 2011 – 15 Jul 2011.

11 Jul 2011, R. Colbeck, R. Renner, T. Stuart, J. A. Slater and W. Tittel, “An experimental test of all theories with predictive power beyond quantum theory”, 20th International Laser Physics Workshop (LPHYS’11), Sarajevo, Bosnia and Herzegovina, 11 Jul 2011 – 15 Jul 2011.

11 Jul 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, W. Tittel, F. Bussières, M. George, R. Ricken and W. Sohler, “A broadband, waveguide quantum memory for entangled photons”, 20th International Laser Physics Workshop (LPHYS’11), Sarajevo, Bosnia and Herzegovina, 11 Jul 2011 – 15 Jul 2011.

18 Jul 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, “Broadband waveguide quantum memory for entangled photons”, 2011 IEEE Photonics Society Summer Topical Meeting, Montréal, Canada, 18 Jul 2011 – 20 Jul 2011.

26 Jul 2011, B. C. Sanders, “Efficient algorithm for optimizing adaptive quantum metrology processes”, Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT11), Prague, Czech Republic, 25 Jul 2011 – 30 Jul 2011.

26 Jul 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, “Broadband waveguide quantum memory for entangled photons”, Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT11), Prague, Czech Republic, 25 Jul 2011 – 30 Jul 2011.

12 Aug 2011, A. MacRae and A. I. Lvovsky, “Remote preparation of arbitrary states of an atomic collective”, Conference on Quantum Information and Quantum Control (CQIQC - IV), Toronto, Canada, 8 Aug 2011 – 12 Aug 2011.

24 Aug 2011, R. Thomas, C. Kupchak, A. Heinrichs and A. I. Lvovsky, “Characterization of a gradient echo memory using homodyne tomography”, Society of Photo-Optical Instrumentation Engineers: Optics and Photonics 2011, San Diego, United States of America, 21 Aug 2011 – 25 Aug 2011.

25 Aug 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, “Broadband waveguide quantum memory for entangled photons”, Society of Photo-Optical Instrumentation Engineers: Optics and Photonics 2011, San Diego, United States of America, 21 Aug 2011 – 25 Aug 2011.

26 Aug 2011, B. C. Sanders, “Swarm intelligence for learning how to do optimal quantum measurements”, Asian Quantum Information Science Conference (AQIS11), Busan, Republic of Korea, 23 Aug 2011 – 30 Aug 2011.

28 Aug 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, “Quantum memory for quantum repeater”, International Quantum Electronics/Lasers and Electro-Optics Conference (IQEC/CLEO Pacific Rim 2011), Sydney, Australia, 28 Aug 2011 – 1 Sep 2011.

4 Sep 2011, D. Oblak, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, M. R. E. Lamont, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, "Quantum memory and entanglement storage in rare-earth ion doped crystals", Ruperto Carola Symposium: Pushing Frontiers in Quantum Information with Atoms and Photons, Heidelberg, Germany, 1 Sep 2011 – 4 Sep 2011.

18 Sep 2011, E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler and W. Tittel, "Quantum memory for quantum repeater", 37th European Conference on Optical Communications (ECOC), Geneva, Switzerland, 18 Sep 2011 – 16 Sep 2011.

1 Oct 2011, A. I. Lvovsky, "Assembling and disassembling light (synthesis, manipulation, measurement and storage of quantum information carried by light)" (plenary), Canadian-American-Mexican Physics Graduate Student Conference, Washington, D. C., United States of America, 29 Sep 2011 – 1 Oct 2011.

23 Oct 2011, B. C. Sanders, "Whither quantum computing?" (plenary), The Eighth International Conference on Progress in Theoretical Physics, Constantine, Algeria, 23 Oct 2011 – 25 Oct 2011.

26 Oct 2011, B. C. Sanders, "Quantum optics in superconducting circuits", The Fourth International Workshop on Theoretical and Computational Nano-Photonics (Tacona - Photonics 2011), Bad Honnef, Germany, 26 Oct 2011 – 28 Oct 2011.

4 Nov 2011, I. Lucio Martinez, P. Chan, N. Lovett, X. F. Mo and W. Tittel, "Towards path optimization in an optically switched quantum network", FREQUENCY Canada-France Meeting Fall 2011, Waterloo, Canada, 4 Nov 2011 – 5 Nov 2011.

4 Nov 2011, J. A. Slater, J. Jin, M. R. E. Lamont and W. Tittel, "Implementations of quantum protocols on optical networks: entanglement & time bin qubits", FREQUENCY Canada-France Meeting Fall 2011, Waterloo, Canada, 4 Nov 2011 – 5 Nov 2011.

7 Nov 2011, W. Tittel, "Mapping quantum states between photons and RE crystals", Shonan meeting on Hybrid Quantum Devices, Shonan Village, Japan, 5 Nov 2011 – 9 Nov 2011.

3 Jan 2012, B. C. Sanders, "Universal quantum simulators for fun & profit" (plenary), The 41st Winter Colloquium on The Physics of Quantum Electronics (PQE - 2011), Snowbird, United States of America, 2 Jan 2012 – 6 Jan 2012.

4 Jan 2012, A. MacRae, T. Brannan and A. I. Lvovsky, "Towards quantum engineering", Physics of Quantum Electronics (PQE 2012), Snowbird, United States of America, 2 Jan 2012 – 6 Jan 2012.

25 Jan 2012, P. M. Leung, A. Blais and B. C. Sanders, "Coherently controlled storage and retrieval of microwave pulses with superconducting artificial atoms", SPIE Photonics West OPTO (OPTO), San Francisco, United States of America, 21 Jan 2012 – 26 Jan 2012.

18 Feb 2012, D. L. Feder, "Mott-insulator transition in coupled cavity arrays", 2012 Canadian Institute for Advanced Research Cold Atoms Meeting (2012 CIFAR Cold Atoms Meeting), Banff, Canada, 15 Feb 2012 – 18 Feb 2012.

20 Feb 2012, A. I. Lvovsky, "Quantum technologies and singularity" (keynote), Global Future 2045, Moscow, Russia, 17 Feb 2012 – 20 Feb 2012.

23 Feb 2012, B. C. Sanders, "Whither quantum computing?", XIV International Symposium of Physics (SIF14), Monterrey, Mexico, 23 Feb 2012 – 25 Feb 2012.

10 Mar 2012, A. I. Lvovsky, "The Russian Quantum Center: a pilot project of setting up basic science in Skolkovo" (keynote), The First International Forum of Russian-speaking Science and Technology Professionals, Cambridge, United Kingdom, 10 Mar 2012 – 11 Mar 2012.

21 Mar 2012, B. C. Sanders and A. Hentschel, "Adaptive quantum measurement via swarm-intelligence machine learning", Research in Optical Sciences, Berlin, Germany, 19 Mar 2012 – 21 Mar 2012.

PATENT

T. Beals and B. C. Sanders, "Distributed encryption methods and systems", assigned serial number US8050410 B2, filed 8 Dec 2006, docket number 038231-004, publication date: 1 Nov 2011.

LINKAGE

COLLABORATION

IQIS and its members have strong linkage with various external organizations and research networks. The IQIS Director is leader of two Canadian research networks on the mathematics of quantum information, one network being with the Network Centres of Excellence for the Mathematics of Information Technology and Complex Systems (MITACS) and the other network being a Collaborative Research Group within the Pacific Institute for Mathematical Sciences (PIMS).

Some IQIS Faculty are members of the Canadian Institute for Advanced Research (CIFAR) Quantum Information Processing Program. IQIS is also strongly involved in the Canadian Innovation Platform 'QuantumWorks'.

IQIS has a strong research effort in quantum communication and cryptography. IQIS is linked to General Dynamics Canada via the Industrial Research Chair in Quantum Communication and Cryptography. IQIS is also part of the France-Canada strategic network "Frequency", which is a binational initiative in quantum cryptography. 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.

International Institutions

Academy of Science of the Czech Republic, Czech Republic
Adam Mickiewicz University, Poland
ETH Zürich, Switzerland
Hewlett-Packard Laboratories, Palo Alto, United States of America
Huaqiao University, People's Republic of China
Indian Institute of Technology, Kharagpur, India
Kazan Physical-Technical Institute of the Russian Academy of Science, Russia
King Khalid University, Saudi Arabia
King Saud University, Saudi Arabia
Louisiana State University, United States of America
Nanjing University, People's Republic of China
Oklahoma State University, United States of America
Paris-Sud 11 University, France
Sharif University of Technology, Iran
Southeast University, People's Republic of China
The Institute for Photonic Sciences, Barcelona, Spain
The National Centre for Mathematics and Physics, King Abdulaziz City for Science and Technology, Saudi Arabia
The University of Queensland, Australia
University of Bristol, United Kingdom
University of Copenhagen, Denmark
University of California at Berkeley, United States of America
University of California at San Diego, United States of America
University of California at Santa Barbara, United States of America
University of Geneva, Switzerland
University of Illinois at Chicago, United States of America
University of Leiden, The Netherlands
University of New South Wales, Australia
University of Paderborn, Germany
University of Science and Technology of China, People's Republic of China
University of Southern California, United States of America
University of Washington, United States of America
Xidian University, People's Republic of China

Canadian Institutions

École Polytechnique de Montréal
National Institute for Nanotechnology
Perimeter Institute for Theoretical Physics
Southern Alberta Institute of Technology
St. Francis Xavier University
Université de Montréal
Université de Sherbrooke
University of Waterloo

University of Calgary

Institute for Biocomplexity and Informatics
Institute for Security, Privacy and Information Assurance
Institute for Sustainable Energy, Environment and Economy

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Mohammad Amin	D-Wave Systems Inc.
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Marcleo Wu	University of Alberta
Shengjun Wu	University of Science and Technology of China
Yijing Zhang	University of Science and Technology of China

TEACHING, TRAINING AND EDUCATION

QUANTUM INFORMATION GRADUATE COURSES

COURSE NAME	INSTRUCTOR	DESCRIPTION
AMAT 601.19 INTRODUCTION TO QUANTUM INFORMATION	G. Gour	Introduction to quantum information theory emphasizing the topics of quantum compression, quantum communication, entanglement, channels, coding, nonlocality, distinguishability, steering, and resources. These topics require basic knowledge of linear algebra.
CPSC 619 QUANTUM COMPUTATION	P. Høyer	Quantum information, quantum algorithms including Shor's quantum factoring algorithm and Grover's quantum searching technique, quantum error correcting codes, quantum cryptography, nonlocality and quantum communication complexity, and quantum computational complexity.
PHYS 615 ADVANCED QUANTUM MECHANICS I	C. Simon	Basic formalism of the theory and its interpretation, symmetry generators. Scattering theory. Bound states. Charged particles in electric and magnetic fields. Approximation methods.
PHYS 677 IMPLEMENTATIONS OF QUANTUM INFORMATION	B. C. Sanders	Proposals and realizations of quantum information tasks including quantum computation, quantum communication, and quantum cryptography in optical, atomic, molecular, and solid state systems.

SERVICES AND OUTREACH

CONFERENCES

MEMBER(S)	COMMITTEE	CONFERENCE/WORKSHOP/ AWARD	LOCATION	CONFERENCE DATES
A. I. Lvovsky	Deputy Chair & Principal Organizer	The Twenty-first Annual International Laser Physics Workshop (LPHYS'12)	Calgary, Canada	23 – 27 July 2012
B. C. Sanders	Deputy Chair, Subcommittee on Quantum Optics	International Quantum Electronics/Laser and Electro-Optics Conference (IQEC/CLEO Pacific Rim 2011)	Sydney, Australia	28 Aug – 1 Sep 2011
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

IQIS PUBLIC LECTURE

The second IQIS Public Lecture was held on 22 September 2011. Professor Sir Peter Knight gave a talk titled “Quantum Technologies for the 21st Century”. Professor Sir Peter Knight FRS is Principal of the Kavli Royal Society International Centre and holds an emeritus position at Imperial College London. He has made numerous contributions to quantum physics, which have been recognized through prestigious awards including the Thomas Young and the Glazebrook Medals of the U.K. Institute of Physics, the Ives Medal of the Optical Society of America, the Royal Medal of the Royal Society and being knighted by the Queen in 2005. Until last year, Sir Peter was Chair of the Defence Scientific Advisory Council at the United Kingdom Ministry of Defence and continues as a science advisor to the U.K. Government. About 170 people participated the event. The event was sponsored by Alberta Innovates - Technology Futures (AITF).

PROFESSIONAL SERVICES

NAME	ROLE	JOURNAL/SOCIETY/ INSTITUTION
A. I. Lvovsky	Associate Editor	*Optics Express*
B. C. Sanders	Co-Chair, Division of Atomic, Molecular, and Optical Physics	Canadian Association of Physicists
B. C. Sanders	Reviewer, Atomic QUantum Technologies (AQUTE) Integrated Project, Information Society and Media, FET – Proactive	European Commission
B. C. Sanders	Evaluator, Information Society and Media, FET – Proactive	European Commission
B. C. Sanders	Member	International Council for Quantum Electronics
B. C. Sanders	Member, Editorial Board	*Mathematical Structures in Computer Science*
B. C. Sanders	Member, Physics Evaluation Group (1505)	National Sciences and Engineering Research Council of Canada
B. C. Sanders	Project Leader, Quantum Information Processing	Networks of Centres of Excellence for Mathematics of Information Technology and Complex Systems
B. C. Sanders	Regional Editor for North America	*New Journal of Physics*
B. C. Sanders	Editor	*Optics Communications*
B. C. Sanders	Chair, Quantum Optical Science and Technology Technical Group	Optical Society of America
B. C. Sanders	Principal Coordinator, Collaborative Research Group for Mathematics of Quantum Information	Pacific Institute for the Mathematical Sciences
B. C. Sanders	Member, Scientific Review Panel	Pacific Institute for the Mathematical Sciences
B. C. Sanders	Member, Editorial Board	*Physical Review A*

MEDIA COVERAGE

SOURCE	TITLE OF ARTICLE	LOCATION	DATE
Nanowerk	Diamonds shine in quantum networks when their impurities are hitched onto nano-resonators: Paul Barclay	online	26 Apr 2011
UToday	Diamonds shine in quantum networks: Paul Barclay	online	28 Apr 2011
Calgary Sun	Alberta research aims to keep information secure: Wolfgang Tittel	online	13 Jul 2011
CBC News	Alberta research aims to keep information secure: Wolfgang Tittel	online	13 Jul 2011
SAIT News & Events	Keeping our information safe for the long term: Wolfgang Tittel	online	13 Jul 2011
UToday	Keeping our information safe for the long term: Wolfgang Tittel	online	14 Jul 2011
Novaya Gazeta	We will decipher all these entangled spaghetti…: Alex Lvovsky	online	21 Jul 2011
CKUA Radio	Cryptography breakthrough produces secure key: Wolfgang Tittel		2 Aug 2011
Phyicsworld.com	Coherent Schrödinger's cat still confounds: Christoph Simon	online	23 Nov 2011
Physorg.com	How to decide who keeps the car: Tossing quantum coins moves closer to reality: Wolfgang Tittel	online	29 Nov 2011
UToday	Deciding who keeps the car: Wolfgang Tittel	online	30 Nov 2011
Vzglyad	World is fundamentally random: Alex Lvovsky	online	22 Feb 2012
Vesti FM	Quantum offers solace only in movies: Alex Lvovsky	online	3 Mar 2012
Vesti FM	Scientists cannot work in cages: Alex Lvovsky	online	10 Mar 2012
Physics Update	Send in the clones: Sadegh Raeisi, Wolfgang Tittel, Christoph Simon	online	22 Mar 2012
Science Daily	Quantum copies do new tricks: Sadegh Raeisi, Wolfgang Tittel, Christoph Simon	online	22 Mar 2012
UToday	Quantum copies do new tricks: Sadegh Raeisi, Wolffang Tittel, Christoph Simon	online	23 Mar 2012
Otkrytaya Gazeta	A photon mosaic: Alex Lvovsky	online	27 Mar 2012

OUTREACH LECTURES

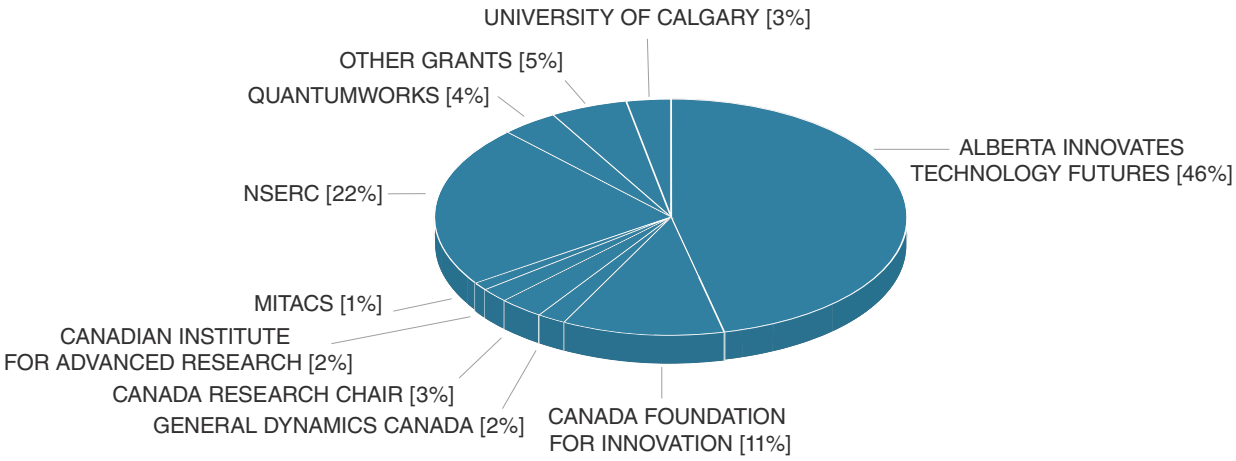
13 Jul 2011, W. Tittel, Demonstration of QKD project to the Honorable Greg Weadick, Chris Pogue (Vice President, GDC), Elizabeth Cannon (President, UofC), Irene Lewis (President, SAIT), and Gary Albach (former CEO, AITF).

23 Nov 2011, W. Tittel, Presentation of QKD to representatives from DRDC and CSEC in Ottawa jointly with Craig Jansen (VP Engineering, GDC) and included a live demonstration of the QKD system.

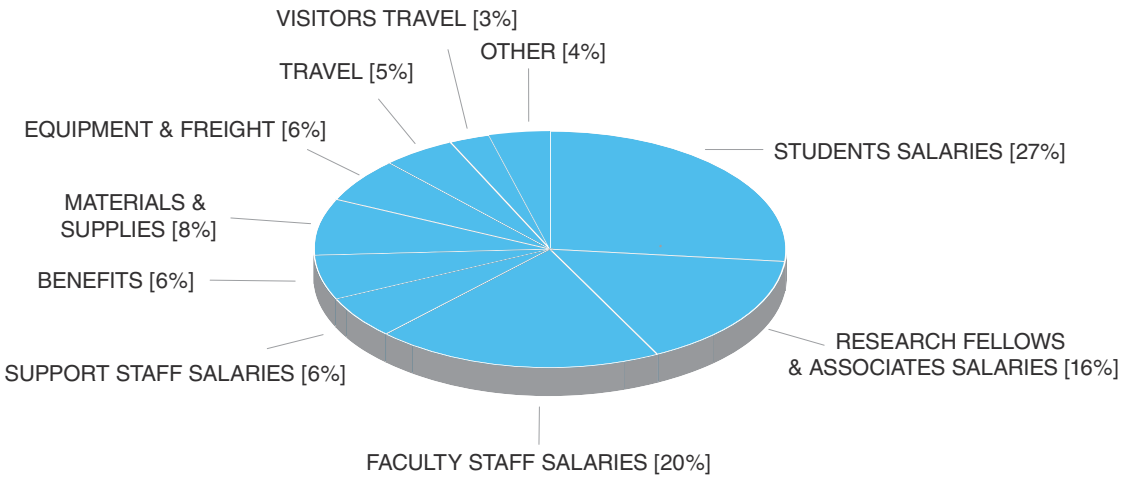
FINANCES

RESEARCH GRANTS (UNAUDITED)

TOTAL REVENUE: $3,236 (IN THOUSANDS)

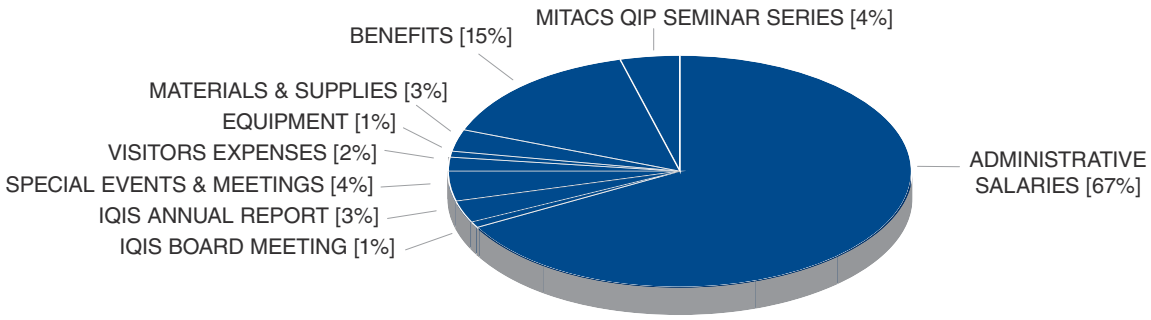


TOTAL EXPENDITURES: $2,565 (IN THOUSANDS)



OPERATING ACCOUNT (UNAUDITED)

TOTAL EXPENDITURES: $95 (IN THOUSANDS)



PLANS AND REQUIREMENTS FOR NEXT YEAR

The plan for 2012-2013 involves major change and expansion of the Institute. The Institute for Quantum Information Science will be renamed and bring on board two more faculty members from the Department of Physics & Astronomy and five more faculty members from the Department of Chemistry. In 2012 the Institute will extend beyond its formidable strength in quantum information science to encompass other University of Calgary strengths in quantum science and technology, including spectroscopy, electronic structure and nanomaterials in the quantum domain.

The Institute will maintain the same governance structure and has received sufficient funding from Alberta Innovates – Technology Futures. This funding enables the transition to a new Institute and support for three years. During these three years, researchers across the quantum spectrum will integrate activities at a world-leading level enhanced by interdisciplinary team building and collaboration.

Several research plans are a high priority for 2012-2013. Quantum cryptography is a high priority for Wolfgang Tittel's group, and in particular development of a high-rate quantum key distribution (QKD) system will continue including integration of two, or possibly four, home-made detectors into a polarization-based system. Furthermore a 2013 target is integration of the QKD system, which is attacker-resistant. A new initiative will be establishing a quantum network across and perhaps beyond Calgary. Quantum memory is central to long-term quantum communication realizations, and, working to this end, candidate media for quantum memory will be thoroughly investigated spectroscopically.

Simon's group has prioritized studies of quantum memory with an emphasis on modulating the refractive index of the host medium. The group will investigate links between this quantum memory approach and electromagnetically induced transparency. The aim is to discover how quantum memory can be used to enhance the performance of quantum information processing such as preparing of heralded multi-photon entanglement. In addition Simon's group will study further the quantum-to-classical transition especially focusing on preparing and detecting macroscopic quantum superpositions of light using squeezing and homodyne detection. Other topics include studying quantum optical nonlinearity based on the interaction of spin waves in Bose-Einstein condensates (in collaboration with Barry Sanders' group), the development and implementation of an error-tolerant quantum private queries protocol (in collaboration with Wolfgang Tittel's group), the study of a source of entangled photon pairs based on hot atomic vapour (in collaboration with Alex Lvovsky's group), and the development of a proposal for

In 2012 the Institute will extend beyond its formidable strength in quantum information science to encompass other University of Calgary strengths in quantum science and technology, including spectroscopy, electronic structure and nanomaterials in the quantum domain.

demonstrating the highly non-local character of Bohmian mechanics using weak measurements.

Alex Lvovsky will be on sabbatical at the Russian Quantum Center in Moscow, where he will set up a quantum optics and information laboratory to complement the one in Calgary. His group in Calgary is focused on full quantum process tomography, quantum light sources and engineering of collective states of atomic ensembles, as well as achieving giant optical nonlinearities using nanofibers and ultracold atoms.

Barry Sanders' group will focus on the following three priorities. Quantum secret sharing is an important means to distribute quantum information in a multi-player setting. Classical secret sharing underpins protocols for electronic voting and electronic auctions, and quantum secret sharing is similarly important to quantum communication. One goal for the coming year is to devise means to cut the cost of quantum secret sharing by borrowing from notions about ramp secret sharing. In ramp secret sharing, the share sizes that go to the various players are below the minimum size required for information-theoretic security yet still can deliver full security when properly exploited. Developing relatively low-cost ramp quantum secret sharing schemes is a high priority in the coming year.

Quantum simulation is now one of the hottest topics in quantum information science as it is likely to enable solving physically important computational problems in the next ten years. One application of these simulations could be to testing theories of condensed matter systems with implications for manipulating and designing new materials. One goal for this group is to devise experimentally-relevant quantum simulation algorithms. These algorithms will accept the permitted error tolerance as an input and produce quantum circuits optimized over all resource costs. Initially the algorithms will focus on simulating many-body systems with components that behave as two-level systems. Another key direction is to devise algorithms for simulating dynamical evolution of open quantum systems, i.e., systems that are not closed but rather interact with their environments. These algorithms are important in that real systems always have environmental effects, and furthermore open-system quantum simulations could address important problems concerning fundamental thermodynamical and statistical mechanical problems.

Another priority of Barry Sanders' group in the coming year is to make significant strides in applications of evolutionary algorithms to quantum metrology. Sanders and his student Hentschel realized the best known quantum adaptive-measurement phase measurement schemes by exploiting

particle swarm intelligence algorithms. Differential evolution offers an alternative promising approach, and the two schemes will be benchmarked against each other in order to ascertain the best evolutionary algorithm approaches and push the simulations to test for more than 100 entangled photons as an input. In another direction the group will test evolutionary algorithms for parameter estimation where the decision tree is not binary but rather increases factorially with each step. This quite-different adaptive scheme will strongly test the efficacy of evolutionary algorithms for quantum metrology.

Gour's group aims to address one of the most fundamental questions in quantum information, namely the amount of information that can be transmitted reliably through a quantum channel. The group will also focus on other problems including whether there exists exotic bipartite mixed states with negative partial transpose and from which it is impossible to distill ebits, optimal strategies to share a quantum secret with a hybrid of quantum and classical shares, optimal ways to share entanglement in quantum networks and necessary and sufficient conditions for local manipulation of multipartite pure states.

Paul Barclay's group is prioritizing the development of photonic devices fabricated from materials suitable for storing quantum information and the demonstration of nanoscale photonics torque sensors. This first goal involves extending the silicon nanofabrication expertise developed during the past year to material systems on the forefront of quantum information science, namely diamond and other wide-bandgap semiconductors. This research will require theoretical investigations into the quantum properties of nanoscale impurities and how they are affected by optically induced changes to their local environment, for example, microscopic strain fields. The second goal involves further improving the performance of silicon optomechanical nanocavities recently developed by the lab and integrating them into systems of practical and fundamental interests. Example systems include an experimental apparatus for probing nanoscale spin currents and practical devices for measuring magnetic fields. The group will be investing effort into recruiting a second postdoc and new graduate students and in moving the lab from its current temporary home to its newly renovated space in the Science B building. This lab move will be coordinated with the setup of a cryogen-free low temperature probing systems optimized for nanophotonics experiments.

Over the next year, members of David Feder's group will focus on theoretical projects at the interface of condensed matter physics, quantum optics and quantum information science. The group will investigate the possibility of generating strongly-correlated states, such as Mott and topological insulators, using atoms confined in optical and microwave cavities. Under different conditions, several of these states are believed to be resources for quantum computation. In addition, the group will study the ground states of strongly interacting quantum many-body systems by means of graph theory and the connections to the theory of perfect quantum state transfer.

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

Labs

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

Offices

ROOM NUMBER	SIZE (SQUARE METER)
ICT 625	13
ICT 625A	13
ICT 626	13
ICT 653	13
MS 364	13
MS 367	12
MS 436	13
MS 544	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

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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