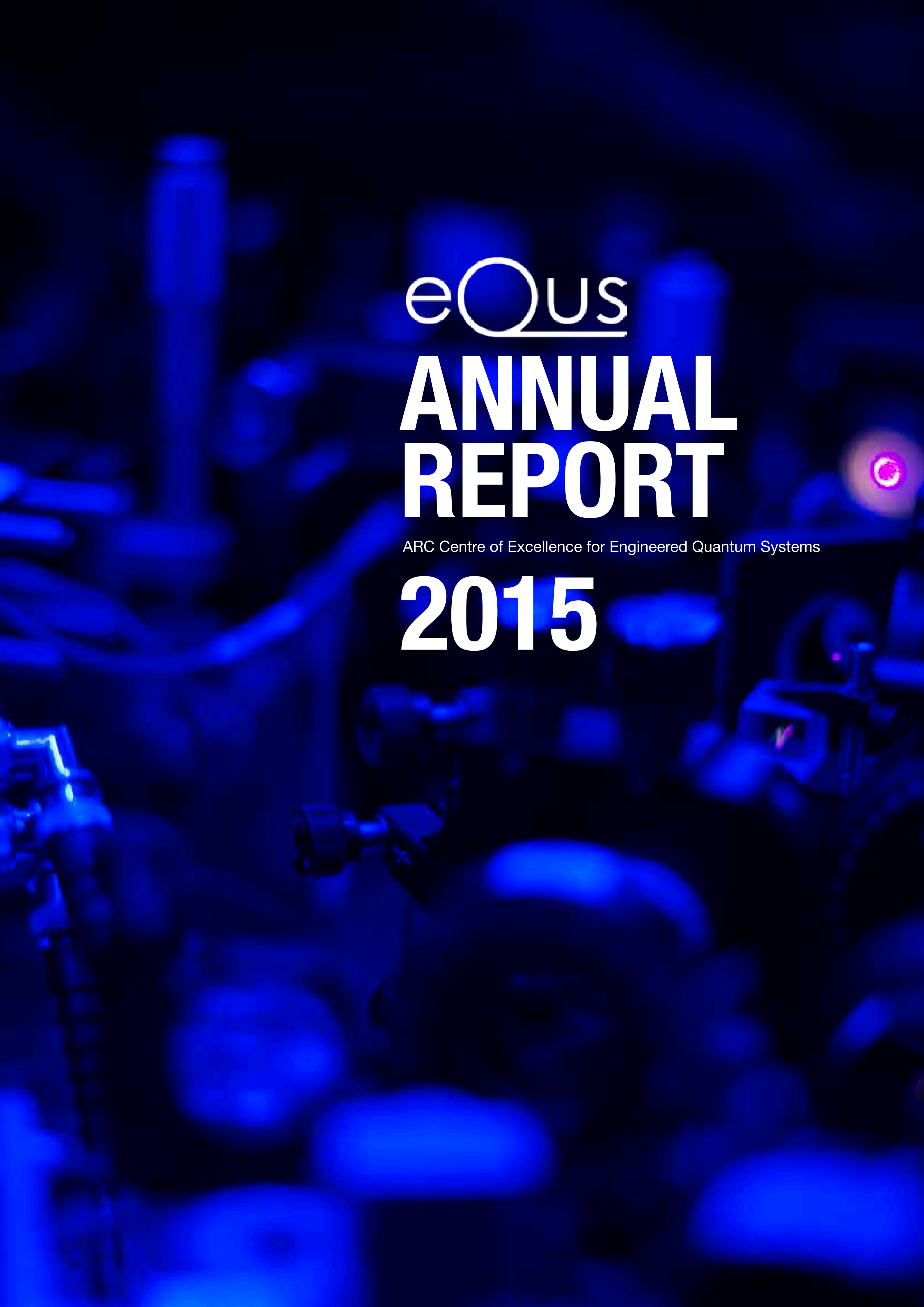

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ANNUAL REPORT

ARC Centre of Excellence for Engineered Quantum Systems

2015

The ARC Centre of Excellence for Engineered Quantum Systems is developing a new field of quantum engineering, which will understand and produce individual quantum systems for technological purposes.

Cover image: Photographer Christina Giarmatzi, "Careful adjustment of quantum photonics by PhD student Markus Rambach".

ACKNOWLEDGEMENTS

EQuS acknowledges the support of the Australian Research Council

Australian Government
Australian Research Council

We also acknowledge the financial and in-kind support provided by our collaborating organisations

The University of Queensland Australia

The University of Sydney

UNSW Australia

The University of Western Australia
Achieve International Excellence

Macquarie University Sydney · Australia

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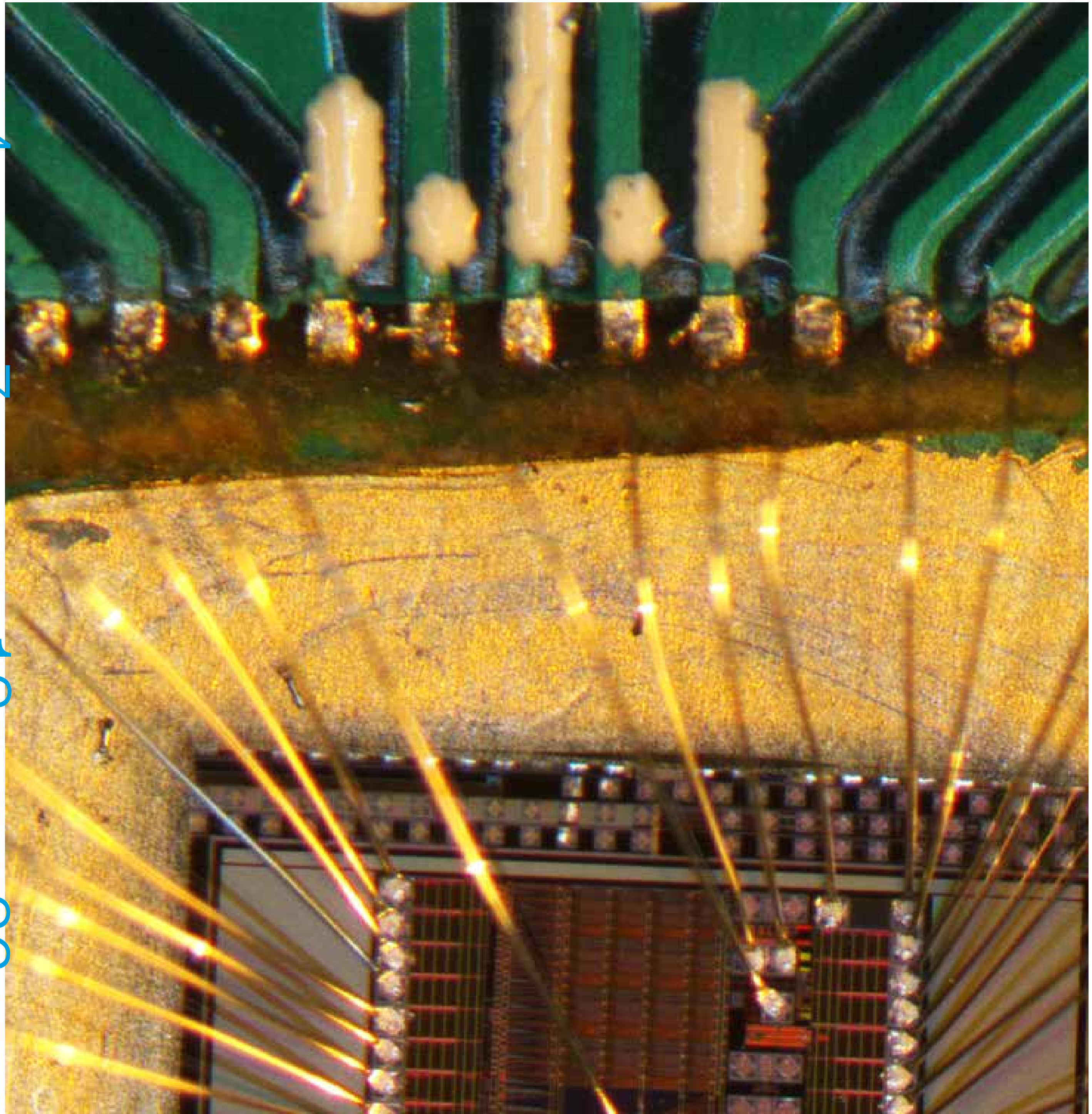

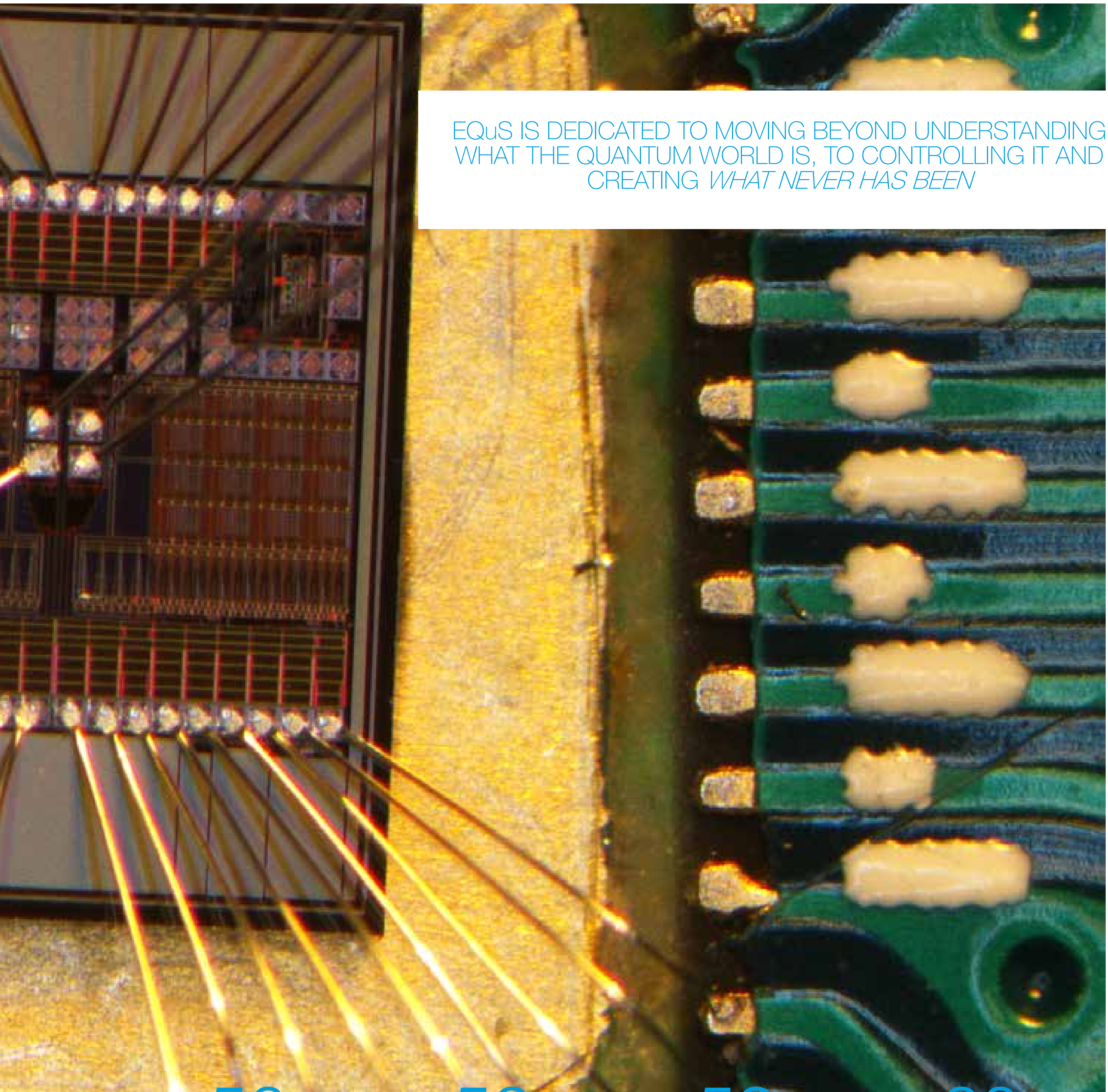

EQuS IS DEDICATED TO MOVING BEYOND UNDERSTANDING WHAT THE QUANTUM WORLD IS, TO CONTROLLING IT AND CREATING *WHAT NEVER HAS BEEN*

Credit: Quantum Nanaoscience Lab, USYD

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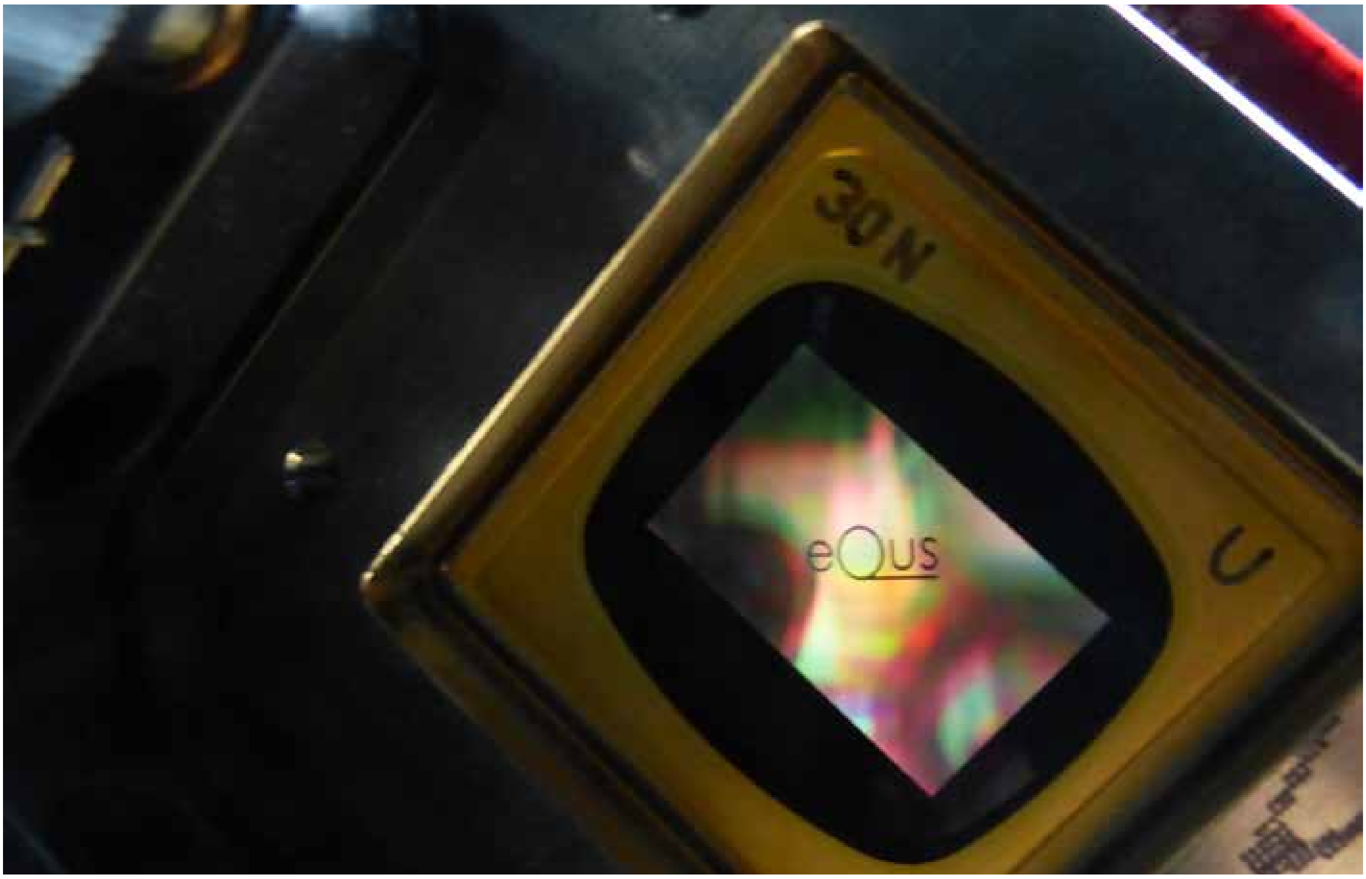
DIRECTOR'S REPORT



In 2015, we made good progress in all three themes, with major achievements in three of our new laboratories (CIs Duty, Fedorov and Volz). Research highlights include:

Quantum measurement & control
CI Bowen's laboratory continued to exploit their discovery of strong optomechanical coupling between a superfluid He thin film and the whispering gallery modes of a toroidal cavity, see the report on page 33. This opens the path to demonstrating superfluid optomechanics in the quantum regime in 2016, which will allow the first demonstration of quantum control of superfluid excitations. CI Reilly continued his investigation of how to implement quantum control in solid-state devices as the complexity of the control task increases. This is a nice example of how new engineering solutions will be required for advances in physics and exactly the kind of project that one would expect to see in a Centre for Quantum Engineering. See Hornibrook et al., Cryogenic Control Architecture for Large-Scale Quantum Computing, Physical Review Applied 3, 024010 (2015).

Quantum-enabled sensors & metrology
CI Reilly's laboratory achieved a high profile publication on their project to use hyper-polarised NV diamond as a means to enhance the sensitivity of magnetic resonance imaging (MRI). This project has been an EQuS flagship from the start and it is very satisfying to see it beginning to make an impact. See Rej et al., Hyperpolarized nanodiamond with long spin-relaxation times, Nature Communications 6, 8459 (2015). CI Volz's laboratory demonstrated a new mechanism for the optical trapping and levitation of diamond nanoparticles based on the cooperative emission for embedded NV centers, see Juan et al., Observation of cooperatively enhanced atomic dipole forces from NV centers in optically trapped nanodiamonds, arXiv:1511.04665.

Synthetic quantum systems & quantum simulation.
CI Duty's group at UNSW achieved a significant result in their new research project in superconducting Josephson junction arrays, showing that single-electron transport dominates deep in the insulating state of Josephson-junction arrays. See Cedergren et al., Parity effect and single-electron injection for Josephson-junction chains deep in the insulating state, Physical Review B 92, 104513 (2015). CI Fedorov's laboratory—using the extraordinary quantum control and measurement efficiency afforded by superconducting circuits—demonstrated the best demonstration to date of quantum non-contextuality, implementing a set of five measurements on the non orthogonal states of a qutrit. CI White's laboratory—using quantum photonics—shed the first experimental light on a debate that stretches back to the foundation of quantum mechanics: is the wavefunction an element of reality or instead a mathematical tool? See Ringbauer et al., Measurements on the reality of the wavefunction, Nature Physics 11, 249 (2015).

As it enters the penultimate year of funding, EQuS is achieving significant results in all of its laboratories with highly innovative parallel theoretical work. Once again, we have surpassed all of our major research KPIs. The founding vision of EQuS is very clearly demonstrated and has established Australia as a world leader in quantum technology.

Professor Gerard Milburn, Director

AS IT ENTERS THE PENULTIMATE YEAR OF FUNDING, EQuS IS ACHIEVING SIGNIFICANT RESULTS IN ALL ITS LABORATORIES WITH HIGHLY INNOVATIVE PARALLEL THEORETICAL WORK

AT EQuS, WE SEEK TO INITIATE THE QUANTUM ERA IN THE 21ST CENTURY BY ENGINEERING DESIGNER QUANTUM SYSTEMS

Centre Overview

Centre Overview

The ARC Centre of Excellence for Engineered Quantum Systems (EQuS) seeks to move from Quantum Science to Quantum Engineering – building and crafting new quantum technologies. The University of Queensland, and the collaborating institutions The University of Sydney, Macquarie University, The University of Western Australia and the University of New South Wales, provide the world's first focussed research program on systems engineering in the quantum regime. EQuS is addressing fundamental questions about the benefits and limits of quantum technologies, developing strategies for producing novel quantum-enhanced devices, and exploring new emergent physical phenomena that arise only in the presence of complex, integrated quantum systems.

Financial Support

The Centre's main source of funding is the Australian Research Council through the Centres of Excellence program. The ARC provides $3.5 million per annum, and the administering institution, The University of Queensland, and the collaborating institutions The University of Sydney, Macquarie University, The University of Western Australia and the University of New South Wales contribute ~$1.2 million in cash contributions per year.

Vision

At the ARC Centre for Engineered Quantum Systems (EQuS) we are engineering the quantum future. By discovering how to control and exploit the most exotic phenomena in quantum theory, our Centre is building a new discipline with the potential to radically transform technology.

Mission

To exploit the vast resources of the quantum realm to produce new capabilities, new technologies, and new science through the creation of designer quantum systems.

Future

Quantum mechanics provides the functionality of nearly every technology around us. Our understanding of this fundamental physical theory has given us the information revolution, home computers, iPhones, GPS, atomic clocks and Magnetic Resonance Imaging (MRI). From flat-panel monitors to optical networks, quantum mechanics has allowed us to engineer the technologies that shape our world.

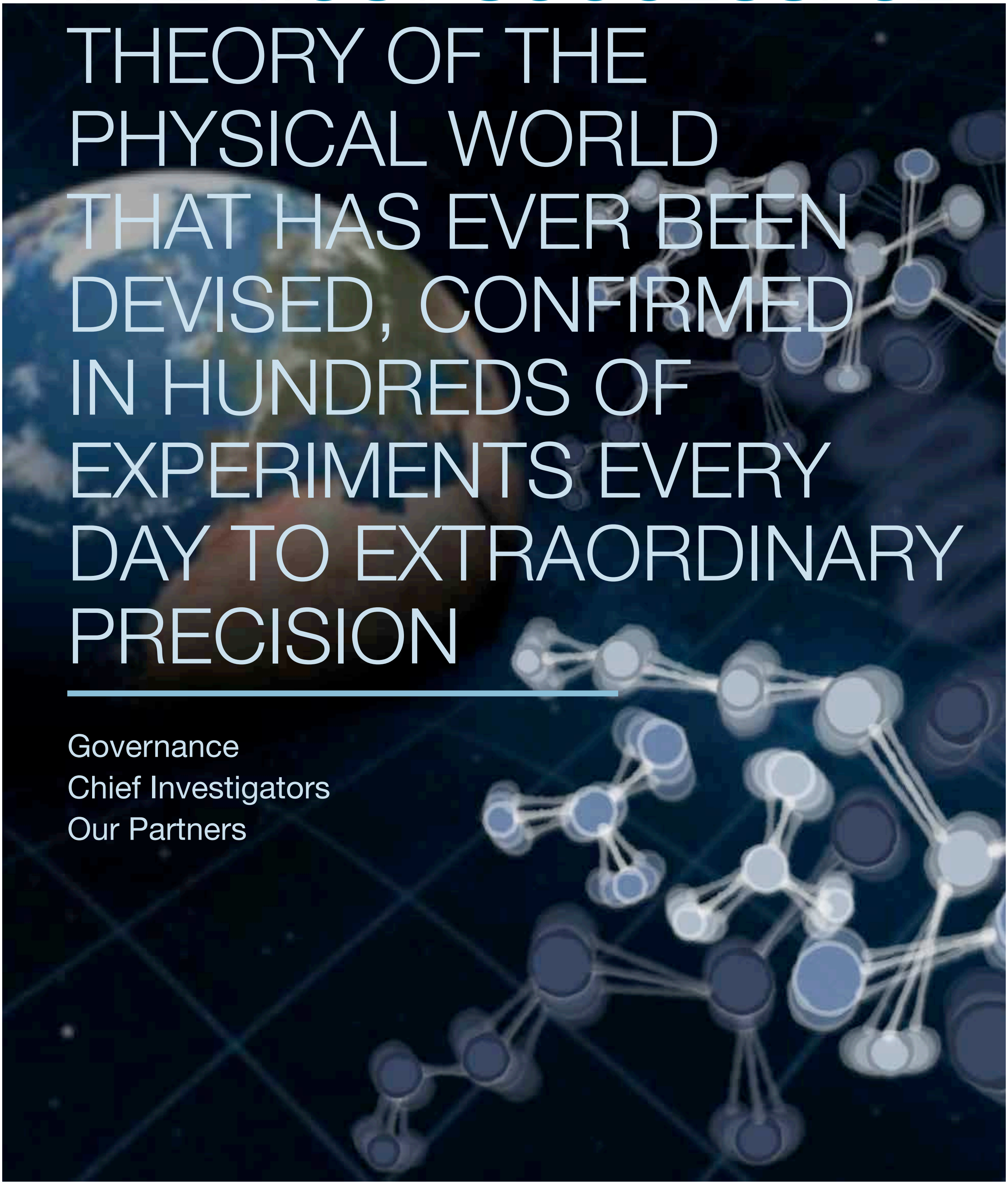
Today's technology only captures a small fraction of the potential in quantum physics. The discovery of quantum revealed a new level for controlling the world, based on manipulating quantum coherence, a new physical feature unknown to pre-quantum physics and the source of puzzling quantum phenomenon like superposition and entanglement. As strange as they appear, these effects have been demonstrated in many experiments.

Quantum technologies are likely to touch all aspects of our lives, from computation to climate science. Our research community has compelling potential applications in mind, but the field is very young and the potential for new inventions based on quantum principles is large.

Over the horizon, we foresee ultra-high precision sensors and detectors for applications in basic science, medicine, environmental monitoring, defence and myriad other sectors. Emerging quantum technologies will enable new ways to simulate complex quantum systems to investigate new quantum phases of matter and provide access to theoretical investigations that are currently impossible. Quantum theory is the most successful theory of the physical world that has ever been devised, confirmed in hundreds of experiments every day to extraordinary precision.

EQuS ADDRESSES FUNDAMENTAL QUESTIONS ABOUT THE BENEFITS AND LIMITS OF QUANTUM TECHNOLOGIES, DEVELOPING STRATEGIES FOR PRODUCING NOVEL QUANTUM-ENHANCED DEVICES, AND EXPLORING NEW EMERGENT PHYSICAL PHENOMENA THAT ARISE ONLY IN THE PRESENCE OF COMPLEX, INTEGRATED QUANTUM SYSTEMS.

QUANTUM THEORY IS THE MOST SUCCESSFUL THEORY OF THE PHYSICAL WORLD THAT HAS EVER BEEN DEVISED, CONFIRMED IN HUNDREDS OF EXPERIMENTS EVERY DAY TO EXTRAORDINARY PRECISION



Governance
Chief Investigators
Our Partners

Organisational Chart

Organisational chart illustrating the governance and management structure of the Centre

EQuS Advisory Board

The Advisory Board consists of 13 members, including an eminent Chair. The Board met twice in 2015 to help create linkages with relevant associations and practitioners, and provided direction on public relations strategies, communications, and translation of knowledge into outcomes. Membership consists of representatives of each Partner Institution and influential people from business and government.

Dr Rowan Gilmore (Chair)
CEO
EM Solutions Pty Ltd

Professor Robyn Ward
DVC Research
The University of Queensland

Professor Sakkie Pretorius
DVC Research
Macquarie University

Professor Duncan Ivison
DVC Research
The University of Sydney

Professor Robyn Owens
DVC Research
The University of Western Australia

Professor Les Field
DVC Research
The University of New South Wales

Ms Lisa Walker
Chief Operations Officer, EQuS
The University of Queensland

Dr Ben Greene
Group CEO
Electro Optic Systems (EOS)

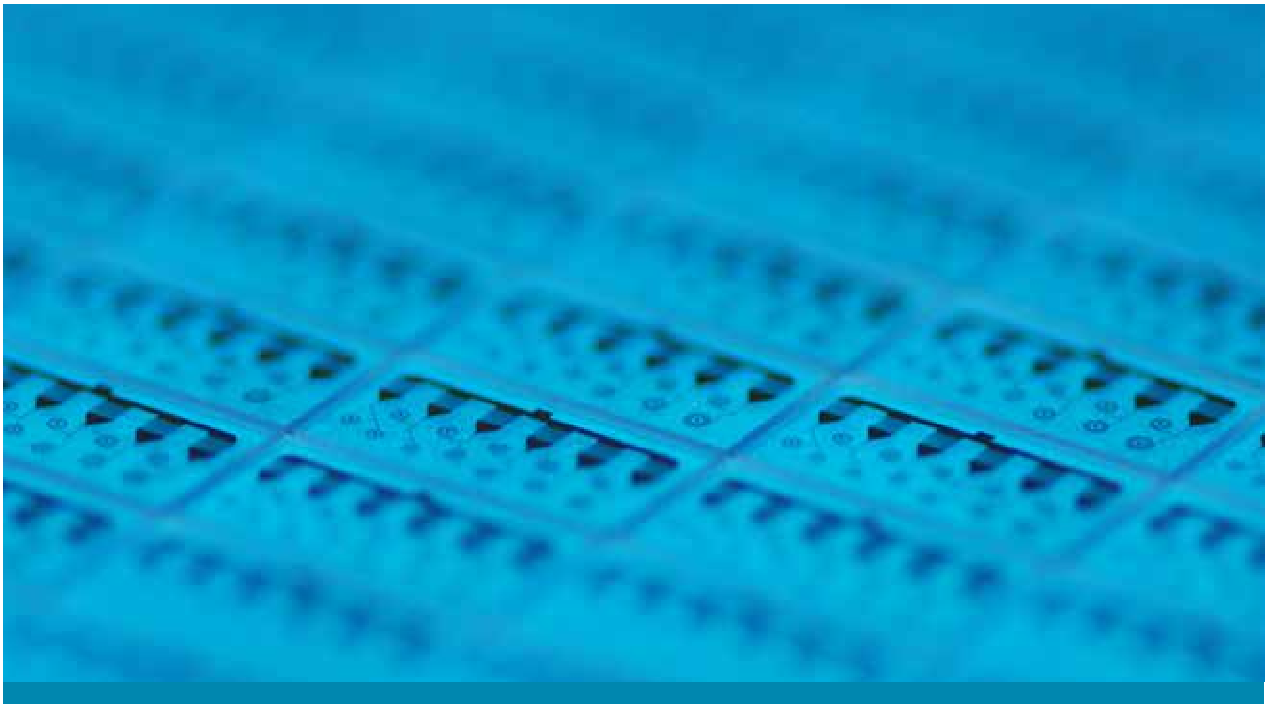
Mr Rick Wilkinson
COO – Eastern Region
Australian Petroleum Production & Exploration Association Ltd

Dr David Pulford
Senior Research Scientist
Defence Science and Technology Group, Department of Defence

Mr Vic Dobos
CEO, Australian Science Teachers Association (ASTA)

Professor Gerard Milburn
Director, EQuS
The University of Queensland

Professor Andrew White
Deputy Director, EQuS
The University of Queensland



Credit: Quantum Nanoscience Lab, USYD

Scientific Advisory Committee

The Scientific Advisory Committee advises the Centre Director on the strategic direction of current and future scientific programs to ensure that these are of the highest quality. It is comprised of eminent researchers from the US, the UK and elsewhere, and meets once a year. The board evaluates the Centre's progress by reviewing annual reports and offering advice on areas for improvement and new research directions.

The Scientific Advisory Committee met at the Annual Workshop in December 2015.

Professor Sir Peter Knight, FRS (Chair), The Kavli Royal Society International Centre and Imperial College London
UK

Professor Mikhail Lukin
Harvard University
USA

Professor John Clarke
University of California, Berkeley
USA

Professor Alain Aspect
Ecole Polytechnique & Institut d'Optique Graduate School
France

Professor Rainer Blatt
Institute for Quantum Optics
University of Innsbruck
Austria

Dr Rowan Gilmore (Advisory Board Chair)
EM Solutions Pty Ltd
Australia

Chief Investigators

CD GERARD MILBURN

EQuS DIRECTOR, UQ

Professor Milburn is one of the pioneers in quantum noise, measurement and control: knowledge of all three is required for the theoretical description of engineered quantum systems. CD Milburn has applied his expertise to a diverse range of technologies, with publications in areas including: quantum optics; quantum information; mescoscopic transport; nonlinear dynamics; ion-traps; atomic Bose-Einstein condensation; optomechanics; and superconducting quantum circuits. In addition, he has published three major monographs in quantum technologies: Quantum Optics, (with Walls), Quantum Measurement and Control (with Wiseman) and Quantum Optomechanics (with CI Bowen).

READ MORE about CD Milburn's research on our website.

CI ANDREW WHITE

EQuS DEPUTY DIRECTOR, UQ

Professor White is a world leader in quantum technology, making significant contributions through his research in the fields of quantum information science and quantum optics. They include both fundamental advances—quantum-logic gates, quantum simulation & emulation, quantum metrology—and methodological advances—entanglement engineering, quantum tomography, and optical vortices. In 1999, he established the world's first quantum technology laboratory to explore and exploit the full range of quantum behaviours—notably entanglement—with an eye to engineering new technologies and scientific applications.

READ MORE about CI White's research on our website.

CI STEPHEN BARTLETT

NODE MANAGER, USYD

Professor Bartlett is pursuing fundamental research in the theory of quantum physics. His particular focus is on quantum information theory, including the theory of quantum computing, as well as the foundational issues of quantum mechanics. CI Bartlett completed his PhD in mathematical physics at the University of Toronto in 2000. Moving to Australia, he directed his research to the theory of quantum computing, first as a Macquarie University Research Fellow and then as an ARC Postdoctoral Research Fellow at The University of Queensland. Since 2005, he has lead a research program in theoretical quantum physics at The University of Sydney, with interests spanning quantum computing, quantum measurement and control, quantum many-body systems and the foundations of quantum theory.

READ MORE about CI Bartlett's research on our website.

CI MICHAEL BIERCUK
USYD

Associate Professor Biercuk is an internationally recognized young leader in the development of quantum control. He is an Experimentalist with experience in condensed matter and atomic physics platforms, currently leading a cutting-edge research program using trapped atomic ions (skills developed working with 2012 Nobel Laureate, David Wineland). CI Biercuk has expertise building and leading large collaborative research programs and is an active leader in public audience discourse on science and science policy.

READ MORE about CI Biercuk's research on our website.

CI WARWICK BOWEN
NODE MANAGER, *UQ*

Professor Bowen is recognised both nationally and internationally for quantum optomechanics, precision measurement, and the translation of quantum technologies. He has made important contributions to the field, including the first demonstrations of quantum enhanced precision and resolution in biological measurements, the concept of cavity opto-electromechanics, photon pair generation from an atomic ensemble, two-dimensional beam positioning below the quantum limit, and strong coupling between a single atom and an integrated microcavity. He has been involved in major international efforts such as the US Air Force Biophysics Program, the DARPA Quantum Assisted Sensing and Readout (QuASAR) and Optical Radiation Cooling and Heating in Integrated Devices (ORCHID) Programs.

READ MORE about CI Bowen's research on our website.

CI GAVIN BRENNEN
MQ

Associate Professor Brennen believes that nature is a wondrous place and an unfinished product. As a result, his main interests are how to use the physical laws we know, particularly quantum mechanics, to probe in ever more exquisite detail the manifestations of nature - from elementary interactions to collective behaviour of complex many particle systems.

READ MORE about CI Brennen's research on our website.

Chief Investigators

CI ANDREW DOHERTY
USYD

Professor Doherty is recognised internationally for his innovative contributions to theoretical physics. He is one of the pioneers of the field of quantum control and has made seminal contributions to quantum information theory. In quantum control he was the first to apply ideas from classical control which is ubiquitous from aircraft to precision measurement to the science of quantum systems. This work was a very early forerunner of the current experimental and theoretical programs in the control of quantum systems. CI Doherty's work emphasised that adaptability and feedback would be essential to any quantum technology and was ahead of its time in emphasising the need to begin engineering quantum systems. CI Doherty is well known for his extensive collaborations with experimentalists in a wide range of systems from quantum optics, including cavity QED and optomechanical systems, to condensed matter, including circuit QED and semiconductor quantum dots.

READ MORE about CI Doherty's research on our website.

CI TIM DUTY
NODE MANAGER, UNSW

Professor Duty is an experimental condensed matter physicist who leads the superconducting device laboratory at The University of New South Wales. He became keenly interested in the quantum physics of superconducting circuits during his postdoctoral research in Germany and Sweden. During this time, he pioneered development of one of the earliest superconducting quantum bits, and novel methods for control and sensing of single-electron transport. From 2011-2015, he was an ARC Future Fellow, focussing on experiments that elucidate quantum phenomena in nano-scale superconducting circuits which incorporate microwaves fields and strongly-correlated charge transport.

READ MORE about CI Duty's research on our website.

CI ARKADY FEDOROV
UQ

Dr Fedorov's research focuses on quantum phenomena in systems consisting of superconducting artificial atoms, microwave resonators and mechanical oscillators.

CI Fedorov has worked in a variety of roles in the area of quantum physics including a three-year stint at TU Delft, The Netherlands conducting experiments with superconducting flux qubits. Later on he became a research scientist at ETH Zurich to continue research in the area of superconducting quantum devices.

READ MORE about CI Fedorov's research on our website.

CI STEVEN FLAMMIA
USYD

Associate Professor Flammia's research interests centre around quantum information theory and applications of the theory to a broad range of topics, including condensed matter theory, topologically ordered phases, tensor networks, error correction, quantum optics, precision metrology, and classical statistical inference and machine learning, specifically compressed sensing. He has made important contributions to the study of characterization, verification and validation of quantum devices.

READ MORE about CI Flammia's research on our website.

CI ALEXEI GILCHRIST
MQ

Associate Professor Gilchrist is a theoretical physicist in the research areas of quantum optics and quantum information. He received his PhD from Waikato University (New Zealand) in 1997 under the supervision of Professor Crispin Gardiner. Moving to Australia in 2001 as a New Zealand FRST Fellow, he remained in Australia as a Research Fellow for the ARC Centre of Excellence for Quantum Computer Technology until becoming part of the faculty at Macquarie University in 2007.

READ MORE about CI Gilchrist's research on our website.

CI IAN McCULLOCH
UQ

Dr McCulloch leads the Tensor Network Algorithms group that works in computational tensor network algorithms for one- and two-dimensional quantum systems, and applications to condensed matter, ultra-cold atomic gases and engineered quantum systems.

CI McCulloch's research interests are numerical techniques for simulating quantum many-body systems, and he is the author of a large suite of software tools that are used by several research groups around the world.

READ MORE about CI McCulloch's research on our website.

CI GABRIEL MOLINA-TERRIZA *MQ*

Associate Professor Molina-Terriza is an Australian Research Council Future Fellow. At Macquarie University, he is the group leader of QIRON (Quantum InteRactiOns with Nanoparticles). His research focusses on the spatial properties of light and uses the spatial modes of light as a tool to probe the properties of nanostructures.

READ MORE about CI Molina-Terriza's research on our website.

CI DAVID REILLY *USYD*

Professor Reilly is the Director of the Quantum Nanoscience Laboratory at The University of Sydney where he leads a group of seven PhD students and three postdoctoral research fellows. The focus of his research is the development of enabling technology to control condensed matter systems at the quantum level.

READ MORE about CI Reilly's research on our website.

CI HALINA RUBINSZTEIN-DUNLOP *UQ*

Professor Rubinsztein-Dunlop has long standing experience with lasers, linear and nonlinear high-resolution spectroscopy, laser micromanipulation, and atom cooling and trapping. She was one of the originators of the widely used laser enhanced ionisation spectroscopy technique and is well known for her recent work in laser micromanipulation.

She has been also working (Nanotechnology Laboratory, Göteborg, Sweden) in the field of nano- and microfabrication in order to produce the microstructures needed for optically driven micromachines and tips for the scanning force microscopy with optically trapped stylus. Recently she led the team that observed dynamical tunnelling in quantum chaotic systems. Additionally, CI Rubinsztein-Dunlop has led the new effort into development of new nano-structured quantum dots for quantum computing and other advanced device related applications.

READ MORE about CI Rubinsztein-Dunlop's research on our website.

CI THOMAS STACE
UQ

Associate Professor Stace completed his PhD at the Cavendish Lab, University of Cambridge in the UK on quantum computing, followed by postdoctoral research at the Department of Applied Mathematics and Theoretical Physics, also at Cambridge. During this time, he was a fellow at Queens' College. He has been at The University of Queensland since 2006, firstly on an ARC Postdoctoral Research Fellowship, then on an ARC Research Fellowship, and was awarded an ARC Future Fellowship in 2014.

His research has largely focussed on applying methods from quantum optics to solid state devices for use in quantum information applications, and more recently on error correction protocols. He also works on high precision measurement in collaboration with experimental colleagues at the University of Western Australia, in a project whose ultimate aim is to contribute to the international definition of Boltzmann's constant and some biophysics.

CI Stace also consults for UniQuest, UQ's commercial arm, on scientific and technical matters.

READ MORE about CI Stace's research on our website.

CI MICHAEL TOBAR
NODE MANAGER, UWA

Professor Tobar is a leading researcher in precision and quantum limited measurement and testing fundamental physics, who has been recognised by many awards both internationally and nationally, as well as giving many invited talks at international conferences. CI Tobar is the focal point of international space missions involving the highest precision clocks in space. He was appointed as the only non-European Science Coordinator of the European Space Agency's (ESA) Atomic Clock Ensemble in Space (ACES) mission on board the International Space Station (ISS).

READ MORE about CI Tobar's research on our website.

CI JASON TWAMLEY
MQ

Professor Twamley is a leading researcher in the theoretical physics of quantum science and technology with a particular emphasis on hybrid quantum systems – systems where one marries together different types of quantum systems to achieve an overall functionality which no one subsystem possesses. CI Twamley originally trained as a lecturer in Ireland and there pioneered many European Union projects focussing on fullerene and diamond based quantum technologies and won a number of EU STREPS and Integrated Projects. Since 2005, CI Twamley has worked at Macquarie University as a Professor of Quantum Information Science and has developed expertise in superconducting, diamond, nanomechanical, magnetic and atomic quantum technologies. His particular focus is on developing quantum sensors where quantum effects can provide society with more precise and functional sensors for use in a variety of settings, examples being magnetometers and inertial sensors. Together with CI Brennen, he conceived of a new field of quantum technology: quantum magneto-mechanics where one uses magnetic fields for levitating and trapping quantum objects.

READ MORE about CI Twamley's research on our website.

CI THOMAS VOLZ
NODE MANAGER, MQ

Dr Volz has successfully worked with different quantum systems, from ultracold quantum gases to integrated quantum photonic devices to nanodiamonds. He has made major contributions to each field. His work on Feshbach resonances in rubidium 87 and the creation and study of ultracold molecules is widely recognised. In quantum photonics, CI Volz demonstrated the creation of strongly correlated photons and ultrafast single-photon switching on a semiconductor chip. CI Volz leads several labs including the Low Temperature Cavity lab at CSIRO and the Nanodiamond Science lab at Macquarie University. The main focus of both labs lies in researching and exploring new ways to fabricate/harness materials which are relevant in quantum technologies. In particular, the main directions at present are quantum sensing with nanodiamonds, nanoscale light-matter interfaces and quantum optomechanics with levitated/trapped nanodiamonds in close collaboration with the Molina-Terriza group at Macquarie University.

READ MORE about CI Volz's research on our website.

EQuS Team

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Jerline Chen (UWA) Node Administrator
Lynne Cousins (MQ) Node Administrator
Ruth Forrest (UQ) Executive Officer to Centre Director
Sandra Fried (UQ) Administration Officer
Natalie Jagals (UWA) Node Administrator
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Daniel King (UQ)
Zhao Lingfei (UWA)
Lachlann Marnoch (MQ)
Ryan Marshman (UQ)
Shram Raual (UQ)

NEW MASTERS BY RESEARCH STUDENTS

Rochelle Martin (MQ) *Collective effects in colour centres in diamond*
Sarath Raman Nair (MQ) *Spin physics of NV- centres in nano-diamonds for high-resolution magnetometry and hybrid quantum systems*
Dean Southwood (MQ) *Quantum simulation algorithms*

NEW PhD STUDENTS

Thomas Boele (USYD) *Using DNP to analyse relaxation patters in nanodiamond*
Ignazio Cristina (USYD) *Storing and retrieving spin-order in arrays of spin-1/2 particles*
Stefan Forstner (UQ) *Quantum mechanics at the macroscale*
Virginia Frey (USYD) *Quantum control with trapped ions*
Thomas Guff (MQ) *Quantum thermodynamics*
Xin He (UQ) *Optimize light-superfluid interaction*
Samantha Hood (UQ) *Electron transport in light harvesting devices*
Angela Karanjai (USYD) *Foundations of quantum information*
Sarah Lau (UQ) *Solid-state entangled photon sources based on silicon-carbide*
Christian Marciniak (USYD) *Quantum simulation with ion crystals*
Aleksandrina Nikolova (UQ) *Building nodes for an entangled quantum network*
Hakop Pashayan (USYD) *Simulating quantum systems*
Jason Pillay (UQ) *Theoretical and numerical methods such as QFT, entanglement entropy, DMRG and QMC, in studying the topological order of strongly correlated quantum systems*
Reece Roberts (MQ) *Quantum-optical trapping of nanodiamonds containing NV centres*
Sam Roberts (USYD) *Symmetry protected topological order in cluster states*
Andres Rosario Hamann (UQ) *Stabilised entanglement in superconducting quantum circuits*
Yauhen Sackhou (UQ) *Extend quantum optomechanics to superfluids-quantum fluids that exist at temperatures close to absolute zero*
Natasha Taylor (UQ) *Theory of delocalised electron transfer*
Behnam Tonekaboni (UQ) *Quantum enhanced metrology with atom-light interactions*
Matthew van Breugel (MQ) *Exploring coherence properties and collective effects in nanodiamonds containing colour centres*
Andrew Wood (MQ) *Exploring the physics of mechanically tunable microcavity polaritons*
Nor Azwa Zakaria (UQ) *Quantum photonic with solid state single photon source*
Cindy Zhao (USYD) *Precise quantum control and quantum memory with trapped ions*

INTERNATIONAL VISITORS

Alexia Auffeves, The French National Centre for Scientific Research
Mario Berta, Caltech University
Alexandre Blais, University of Sherbrooke
Rainer Blatt, The University of Innsbruck
Robin Blume-Kohout, Sandia National Laboratories
Matthias Brandl, The University of Innsbruck
Hans Briegel, The University of Innsbruck
Daniel Browne, University College London
Thomas Busch, Okinawa Institute of Science and Technology Graduate University
Pavel Bushev, Experimentalphysik Universität des Saarlandes
Carlton Caves, University of New Mexico
Ulysse Chabaud, ENS de Lyon
Ninnat Dangniam, University of New Mexico
Andrew Darmawan, University of Sherbrooke
Leandro Aparecido Nogueira de Paula, Universidade de São Paulo
Tommaso Demarie, Singapore University of Technology & Design
Jon Dowling, Louisiana State University
Adrien Feix, University of Vienna
Serge Galliou, Dept TF FEMTO-ST Institution
Alexander Glätzle, Institute for Quantum Optics & Quantum Information of the Austrian Academy of Sciences
Hsi-Sheng Goan, National Taiwan University
Michael Goggin, Truman State University
Jeffrey Grover, Massachusetts Institute of Technology
Simon Gustavsson, Massachusetts Institute of Technology
Cornelius Hempel, The University of Innsbruck
Bas Henson, Indiana University
Eddie Hung, Imperial College
Sofyan Iblisdir, University of Barcelona
Fedor Jelezko, The University of Ulm
Victor Jimenez, University of Southampton
Tomas Jochyn-O'connor, University of Waterloo
Yogesh Joglekar, Indiana University
Richard Kueng, University of Freiburg
Yi-Chan Lee, University of National Tsing Hua
Chi-Kwong Li, University of Waterloo
Marco Liscidini, University of Pavia
Nana Liu, Oxford University
Rob Mann, University of Waterloo
Bill Munro, NTT Basic Research Laboratories
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Kae Nemoto, National Institute of Informatics
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David Poulin, University of Sherbrooke
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Alessandro Romito, Free University of Berlin
Mark Rudner, Niels Bohr Institute
Terry Rudolph, Imperial College
Mateus Araujo Santos, University of Vienna
Joerg Schmiedmayer, Vienna University of Technology
Robert Sewell, The Institute of Photonic Sciences
Jacob Taylor, University of Maryland
Peter Turner, University of Bristol
Leiven Vandersypen, DELFT University of Technology
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Ian Walmsley, University of Oxford
Stephanie Wehner, DELFT University of Technology
Stephan Weis, Institute of Mathematics, Statistics and Scientific Computing, Campinas, Brazil
Dominic Williamson, University of Vienna
David Wineland, National Institute of Standards and Technology Physics Laboratory
Christopher Wood, University of Waterloo
Fei Yan, Massachusetts Institute of Technology
Lingfei Zhao, Nanjing University

EQuS TEAM

19 CHIEF INVESTIGATORS

54 RESEARCHERS (incl. ECR)

12 PROFESSIONAL STAFF

83 HIGHER DEGREE RESEARCH

14 HONOURS

26 NEW RHDs IN 2015

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Duke University, Durham, USA
Massachusetts Institute of Technology, Massachusetts, USA
Dartmouth College, Hanover, USA
Canadian Institute for Advanced Research (CIFAR), Quantum Information Science, Toronto, Canada
Department of Physics and Astronomy, University of Waterloo, Canada
Department of Physics, University of Sherbrooke, Canada
Institute for Quantum Computing (IQC), University of Waterloo, Canada
Institute for Quantum Science and Technology (IQST), University of Calgary, Canada
Perimeter Institute for Theoretical Physics, Waterloo, Canada

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National University of Science and Technology MISIS

THE UKRAINE

Institute of Radio Astronomy of National Academy of Sciences of Ukraine
O.Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine
School of Radio Physics, V.N. Karazin Kharkiv National University

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Collaborative Innovation Center of Quantum Matter
College of Physics and Energy, Fujian Normal University
Computational Science Research Center
Department of Physics, East China University of Science and Technology
Department of Physics, Zhejiang University
State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University
State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences
State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences
Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China
The School of Science, Southwest University of Science and Technology

TAIWAN, JAPAN & SINGAPORE

Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Taiwan
Department of Physics, National Chung Hsing University, Taiwan
Institute of Physics and Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan
National Center for Theoretical Sciences, Physics Division, National Tsing Hua University, Taiwan
NTT Basic Research Laboratories, NTT Corporation, Japan
NII, National Institute of Informatics, Japan
Centre for Quantum Technologies, National University of Singapore, Singapore
Quantum Measurement Group, National University of Singapore, Singapore
Singapore University of Technology and Design, Singapore

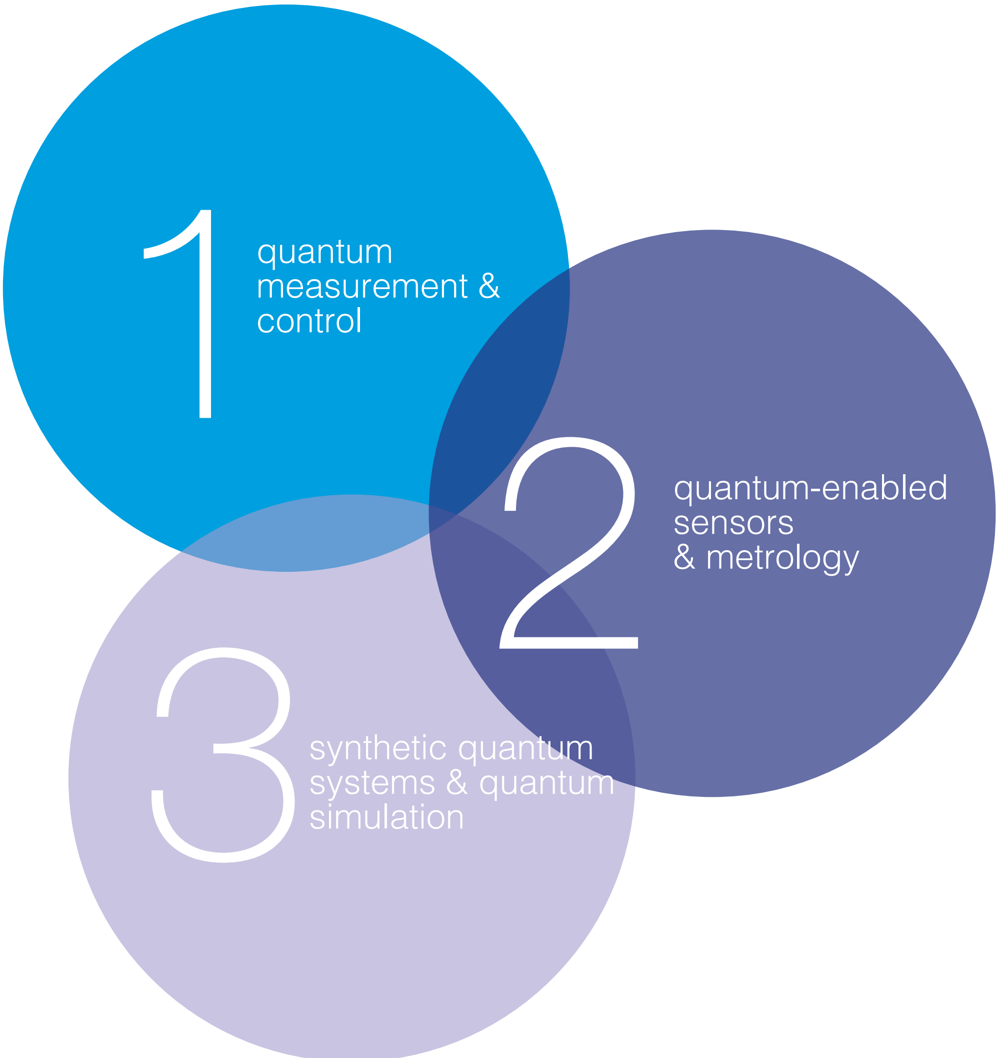
AUSTRALIA

ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T)
ARC Centre of Excellence for Nanoscale Biophotonics (CNBP)
ARC Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)
Centre for Health Technologies (CHT), University of Technology Sydney
Centre for Quantum Computation and Intelligent Systems (QCIS), University of Technology Sydney
Chemical and Quantum Physics, School of Applied Sciences, RMIT University
Department of Chemistry and Biomolecular Sciences, Macquarie University
Department of Physics and Astronomy, Macquarie University
Institute for Photonics and Advanced Sensing (IPAS), University of Adelaide
MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University
National Measurement Institute (NMI)
Research School of Engineering, The Australian National University
School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University
School of Electrical Engineering and Telecommunications, University of New South Wales
School of Mathematics and Physics, The University of Queensland
School of Physics, Monash University
School of Physics, The University of Western Australia
School of Physics, University of Sydney
School of Physics, University of New South Wales

WE NEED TO LEARN HOW TO ENGINEER THE QUANTUM WORLD TO OUR PURPOSE. THIS IS THE MISSION OF THE ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

EQuS Research

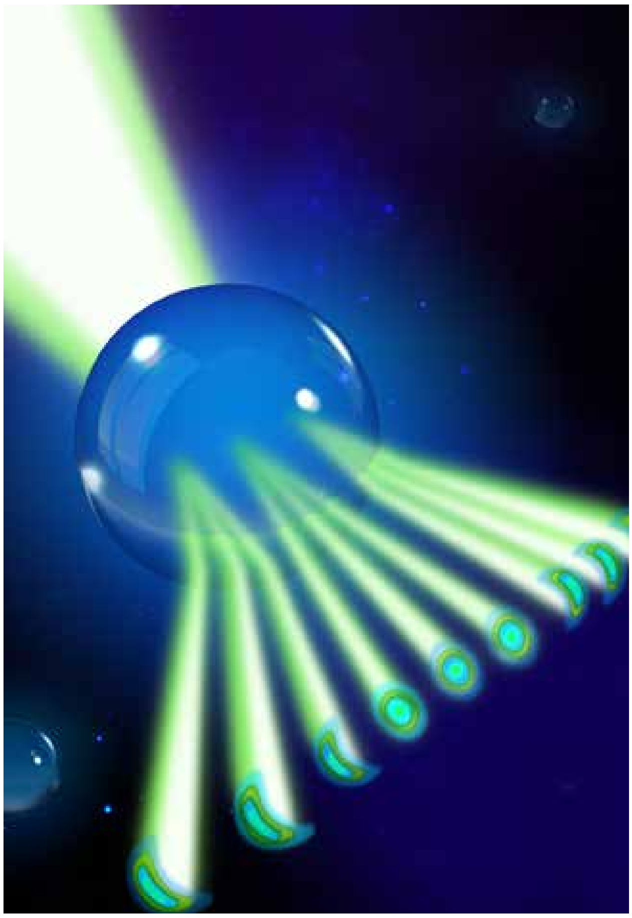
EQuS research is organised around carefully crafted research themes and individual projects



'Engineered' refers to our attitude to quantum physics. We are dedicated to moving beyond understanding what the quantum world is, to controlling it and creating what never has been. Driven by advances in technology and experimental capability, it is now possible to engineer complex, multi-component systems that merge the once distinct fields of quantum optics and condensed matter physics.

Examples of engineered quantum systems include quantum nano-mechanical and opto-mechanical systems and superconducting quantum circuits with applications in precision measurement and quantum computation.

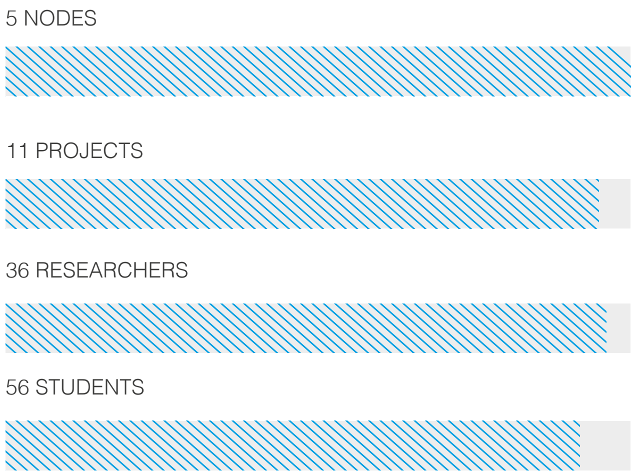
THROUGH FOCUSSED AND VISIONARY RESEARCH WE WILL DELIVER NEW SCIENTIFIC INSIGHTS AND FUNDAMENTALLY NEW TECHNICAL CAPABILITIES ACROSS A RANGE OF DISCIPLINES.

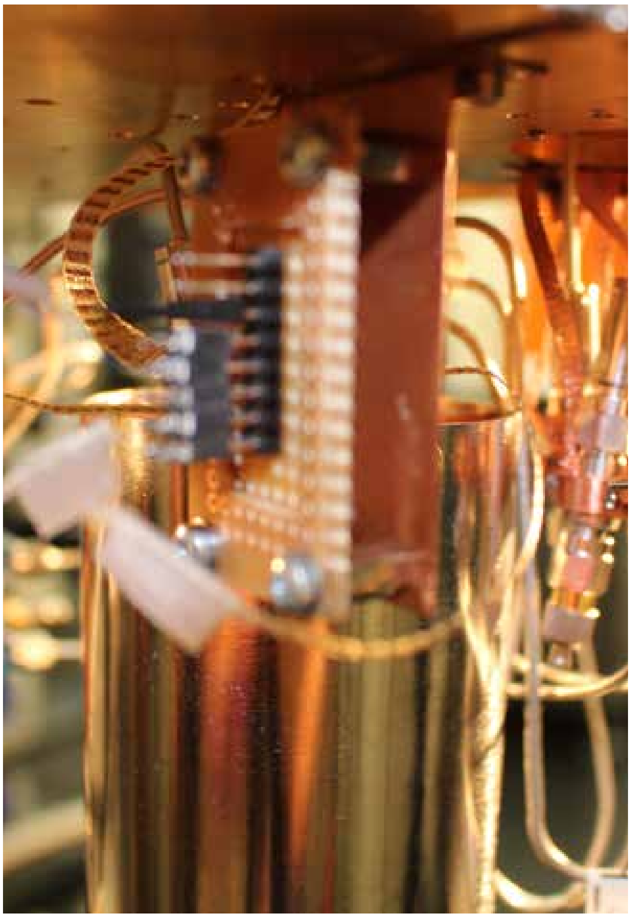


QUANTUM MEASUREMENT AND CONTROL

Precision measurement technology underpins scientific discovery and is an enabler of new technologies. Improving accuracy for the measurement of time lies at the heart of our modern world and is central to our work.

We are addressing scientific challenges in the field of quantum limited measurement and control in an effort to dramatically expand the functionality of engineered quantum systems and provide innovative solutions to major challenges facing the realisation of quantum-enabled technologies





QUANTUM-ENABLED SENSORS AND METROLOLGY

Physical systems that are strongly governed by quantum effects can serve as exquisitely sensitive detectors. We are delivering unprecedented levels of sensitivity and precision in applications of quantum systems for sensing, biomedical imaging and metrology.

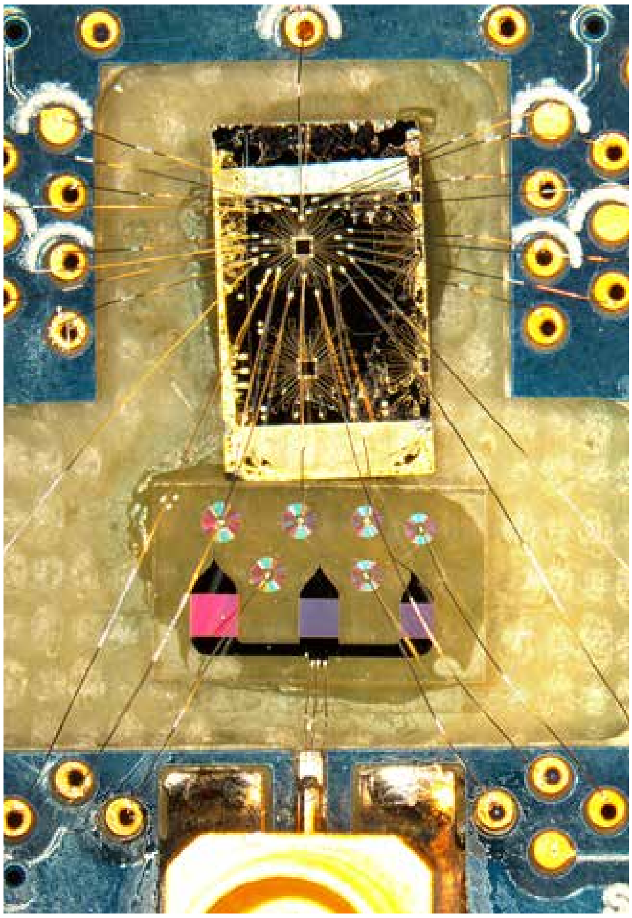
We are addressing scientific challenges in the field of quantum-enabled sensors and metrology.

3 NODES

5 PROJECTS

31 RESEARCHERS

23 STUDENTS



SYNTHETIC QUANTUM SYSTEMS AND QUANTUM SIMULATION

We are producing novel states of light and matter exhibiting strong quantum mechanical correlations that enable simulations of complex interacting quantum systems.

We are addressing scientific challenges in synthetic quantum systems and quantum simulation.

3 NODES

7 PROJECTS

18 RESEARCHERS

27 STUDENTS

QUANTUM MEASUREMENT AND CONTROL

weblink

ADDRESSING SCIENTIFIC CHALLENGES IN THE FIELD OF QUANTUM LIMITED MEASUREMENT AND CONTROL

CHIEF INVESTIGATORS

» Stephen Bartlett
» Michael Biercuk
» Warwick Bowen
» Andrew Doherty
» Tim Duty
» Arkady Fedorov
» Steven Flammia
» Gerard Milburn
» Gabriel Molina-Terriza
» David Reilly
» Halina Rubinsztein-Dunlop
» Thomas Stace
» Michael Tobar

SNAPSHOT FOR 2015

1. Error suppression in two-qubit gates
2. Controlling quantum systems
3. Understanding the impact of noise correlations in randomized benchmarking
4. Single photon optomechanics
5. Hybrid photon-spin resonant structures
6. Hybrid high-Q acoustic oscillators/resonators
7. Low noise microwave and millimetre wave devices for reading out extremely small transducer signals
8. Quantum plasmonics
9. Testing quantum contextuality with superconducting circuits
10. Quantum optomechanics
11. Coulomb blockade and dual Josephson effects in nano-structured, superconducting 1D junction chains and SQUID arrays.

Error suppression in two-qubit gates

Michael Biercuk (CI), Todd Green

This work addresses a problem of fundamental physical and technological significance – suppressing error in entangling quantum logic gates. Entangling logic operations are of tremendous importance to the field of quantum information, which attracts broad interest in the physics community. Moreover, dealing with error is a significant hurdle in the development of quantum technologies and has attracted significant attention in the community.

In this project, we developed a technique suppressing residual entanglement between spin and bosonic oscillator modes at the conclusion of a gate operation. This is a limiting source of error in many quantum logic operations, including Molmer Sorensen gates in trapped ions, and phase gates in superconducting qubits.

Our technique relies exclusively on discrete phase shifts in an intermediary driving field generating the entangling operation in order to both decouple the spin and bosonic mode and to suppress time-dependent errors in the operation.

Our method is technologically simple and permits analytic calculation of the relevant control parameters. Importantly, we have shown that the implementation in realistic settings of multiple trapped ion qubits interacting with multiple modes, permits gate realization with protection in times shorter than existing protocols. Our method also obviates technically challenging complications in previously demonstrated techniques using numerical optimization and amplitude modulation of laser pulses.

The results we presented are directly applicable to a range of real experimental systems including trapped ions, superconducting qubits coupled to cavities, and optomechanical systems. Results were published as:

T. J. Green and M. J. Biercuk, "Phase-modulated decoupling and error suppression in qubit-oscillator systems," arXiv:1408.2749 Physical Review Letters 114 120502 (2015).

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Credit: EQuS researcher Dr Tyler Neely

OUR METHOD IS TECHNOLOGICALLY SIMPLE AND PERMITS ANALYTIC CALCULATION OF THE RELEVANT CONTROL PARAMETERS

Controlling quantum systems

Stephen Bartlett (CI), Andrew Doherty (CI), Steven Flammia (CI), Christopher Ferrie, Christopher Granade, Robin Harper, Matthew Wardrop, Michael Biercuk (CI), Tom Stace (CI)
Collaborators: Andrew Dzurak (UNSW), Joel Wallman (Waterloo), Andrew Ferguson (Cambridge)

The Controlling Quantum Systems program at the University of Sydney aims to develop practical techniques for the measurement and control of engineered quantum systems. The emphasis is on applying theoretical ideas from areas such as randomized benchmarking, quantum feedback control and Hamiltonian parameter estimation to experimental settings to enable the demonstration of prototype engineered quantum systems.

In 2015, we made significant progress in understanding how coherent errors and noise correlations affect randomized benchmarking which is the standard benchmark for verifying the performance of quantum devices. We collaborated with colleagues at the ARC Centre of Excellence for Quantum Computation and Communication Technology to demonstrate benchmarking of single qubit devices in silicon semiconductor qubits. This work successfully demonstrated that the effects of low-frequency noise can indeed be detected in practice in experimental implementations.

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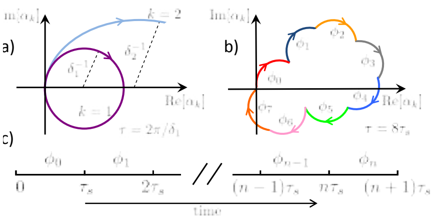
Understanding the impact of noise correlations in randomized benchmarking

Michael Biercuk (CI), Thomas Stace (CI), Steven Flammia (CI), Harrison Ball

In 2015, we initiated a new collaborative project between the Quantum Control Laboratory at the University of Sydney and the group of CI Tom Stace at The University of Queensland. This work sought to provide new theoretical insights into the behaviour of a well known and widely used quantum characterization technique known as randomized benchmarking (RB) when key underlying assumptions were violated. This is not simply a vanity exercise – the violation of the key assumption of uncorrelated errors occurs with regularity in laboratory environments, yet the impact of temporal correlations on this metric were completely unknown.



Our work consisted of detailed analytic and numeric studies providing evidence that operational fidelities derived from randomized benchmarking can suffer biases that artificially inflate reported single-qubit gate fidelities derived from experiments. Moreover, our work revealed that there can be a substantial breakdown between the applicability of randomized-benchmarking error rates and error parameters relevant to fault-tolerance (e.g. worst-case errors) when the assumption of statistically independent error processes is violated. Our work validated other studies demonstrating that in the limit of strongly correlated error models worst case errors can be far larger than mean errors. On the basis of our analytic results, we suggested concrete recommendations for experimental reporting of randomized benchmarking statistics and provide new bounds on the interpretation of experimental results.

The analytic treatment we provide - substantiated by numerical simulations of randomized benchmarking outcomes - revealed the underlying mechanism for the differential accumulation of error in randomized benchmarking sequences subjected to either uncorrelated or correlated error processes. Outside of randomized benchmarking, our results represented an original physical insight into the dynamic evolution of a controlled quantum system subject to imperfect non-commuting controls. The geometric interpretation of error accumulation we developed - treating error accumulation as a random walk in a 3D Pauli Space - is likely to impact other areas of quantum dynamics and quantum information.

Results were published in *Physical Review A* as:
H. Ball, T.M. Stace, S. Flammia and M. J. Biercuk, "The effect of noise correlations on randomized benchmarking," arXiv:1504.05307. Physical Review A 93, 022303 (2015).

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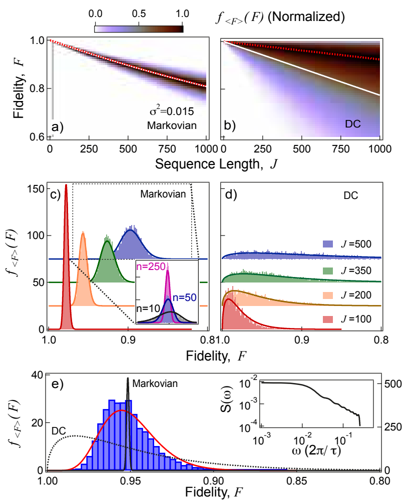

Single photon optomechanics

Gerard Milburn (CI), Sahar Basiri, Casey Myers
Collaborators: Josh Combes

Single photon states exhibit highly non-classical interference effects such as Hong-Ou-Mandle interference. We discovered a procedure to control this kind of interference by injecting single photons into coupled optical cavities with the coupling modulated by mechanical vibrations. This enables photons to be periodically converted to vibrational quanta. When the mechanical resonator is close to its ground state, it acts as a quantum control, entangling the optical and mechanical degrees of freedom. As the coherent amplitude of the resonator increases, we recover single photon and two-photon interference via a classically controlled beam splitter. This mechanically induced coherent photon conversion scheme provides a new route to use optomechanics to produce multi-quanta complex photonic states with applications in photonic quantum information processing.

READ MORE

Hybrid photon-spin resonant structures

Michael Tobar (CI), Maxim Goryachev, Jean-Michel Le Floch, Warrick Farr, Natalia Carvalho, Daniel Creedon, Jeremy Bourhill, Nikita Kostylev
Collaborators: Stefania Castelletto, Jerzy Krupka, Pavel Bushev, Ray Simmonds, Joe Aumentado, John Teufel

Novel resonant photonic structures continue to be under investigation, including 3D lumped LCR reentrant cavities and lattices, whispering gallery mode cavities and TE-mode cavities. Research was undertaken to implement new hybrid quantum systems using these tools and achieve strong coupling in the single photon regime.

1. Special two-mode 3D reentrant cavities were invented and coupled strongly to defects in diamonds.
2. Multi-mode lattices were built and new ideas for multi-mode magnetic and electric coupling of photons proposed.
3. In YSO new strongly coupled spin transitions were discovered, and for the first time the microwave dielectric properties were characterized.
4. Rare-Earth ferromagnetic phase transition was measured in YAG by observing the spin-photon interactions, strong coupling was also obtained.
5. The low temperature properties of Lithium Niobate and Fe^{3+} doped Lithium Niobate were measured for the first time. The potential as a microwave to optical transducer was assessed.
6. Collective superradiant behaviour of Cr^{3+} in ruby was observed in ruby.
7. Qubit transmons were coupled to sapphire whispering gallery mode resonators.

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Hybrid high-Q acoustic oscillators/ resonators

Michael Tobar (CI), Arkady Fedorov (CI), Gerard Milburn (CI)
Collaborators: Serge Galliou (FEMTO-ST), John Clarke (Berkeley), Holger Mueller (Berkeley)

During 2015, we continued to research single crystal Bulk Acoustic Wave resonators of gram scale mass. To gain quantum-limited readout, we have investigated coupling superconducting circuits to these devices.

1. Maxim Goryachev visited John Clarke's lab in Berkeley for two months to build a SQUID amplifier, to allow readout of Bulk Acoustic Wave motion near the quantum limit. The system was built, now a low noise current source is under construction.

2. At the American Physical Society's March 2016 meeting Dr Matt Woolley together with CIs Milburn and Federov, will present a proposal for publication to couple to Bulk Acoustic Wave motion via a transmon qubit mediated by a tunable superconducting LC circuit. In theory this was shown that the system could be cooled to its ground state.

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Low noise microwave and millimetre wave devices for reading out extremely small transducer signals

Michael Tobar (CI), David Reilly (CI), Romain Bara-Maillet, Stephen Parker

Unlike nano-scale devices, to read out large gram scale acoustic oscillators at the quantum limit, the lowest noise oscillators and readouts have to be developed. This is because the signals are in general orders of magnitude smaller. UWA had one PhD completion (Romain Bara-Maillet), who studied important aspects of low noise oscillators and devices.

Romain Bara-Maillet also spent many months in the Quantum Nanoscience Laboratory (QNL) led by CI Reilly at the University of Sydney. He performed measurements on instruments typically used by the quantum computing community as sources for qubits gates and tested successfully in a cryogenic environment. Progress on the design of the LNA resulted in the selection of pHEMT discrete transistor usable at 4 K.

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Quantum plasmonics

Gabriel Molina-Terriza (CI), Alexander Buese, Nora Tischler, Xavier Vidal, Mathieu Juan
Collaborators: Javier Aizpurua, Fabio Sciarrino, Lorenzo Marrucci

EQuS is contributing to the rapid growth of the field of quantum plasmonics through the activities of the Macquarie group. The objective of this field of research is to achieve a quantum control of the metallic nanostructures which are currently being used, for example as precise biosensors. By controlling the quantum state of such systems, we will be able to improve the resolution of these devices and also bring them to applications in quantum processing at the nanoscale. This year has been particularly productive for our EQuS team in this field, as we have for the first time achieved one of the landmarks that we set at the start of the Centre. For the first time, our team has managed to probe single nanoparticles with entangled photons. This kind of system is very versatile, as it allows to use the mature quantum state preparation of photonic systems to address the plasmonic nanostructures. This system can be used to perform quantum measurements of the nanostructures which would be otherwise be inaccessible to classical light due to the diffraction limit.

FOR THE FIRST TIME WE HAVE ACHIEVED ONE OF THE LANDMARKS THAT WE SET AT THE START OF THE CENTRE

Moreover, our team has managed to demonstrate that, even though the structures are smaller than the wavelength of light, they can differentiate between different entangled states. This discovery is relevant from a fundamental point of view, showing that photonic entanglement can survive even when interacting with nanostructures, and also for applications in quantum control, showing that nanostructures can respond differently to different quantum states, opening the door to a quantum nanoprocessing of light.

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Testing quantum contextuality with superconducting circuits

Arkady Fedorov (CI), Markus Oppliger, Anton Potocnik, Mintu Mondal, Andreas Wallraff (ETH Zurich, Switzerland), Kenneth Goodenough, Stephanie Wehner, Nathan K. Langford, Kristinn Juliusson (CEA Saclay, France)

Quantum physics cannot be reconciled with the classical philosophy of noncontextual realism. Realism demands that system properties exist independently of whether they are measured, while noncontextuality demands that the results of measurements do not depend on what other measurements are performed in conjunction with them. The Bell-Kochen-Specker theorem states that noncontextual realism cannot reproduce the measurement statistics of a single three-level quantum system (qutrit). Noncontextual realistic models may thus be tested using a single qutrit without relying on the notion of quantum entanglement in contrast to Bell inequality tests. It is challenging to refute such models experimentally, since imperfections may introduce loopholes that enable a realist interpretation. Using a superconducting qutrit with deterministic, binary-outcome readouts, we violate a noncontextuality inequality while addressing the detection, individual existence and compatibility loopholes. Noncontextuality tests have been carried out in a range of different physical systems and dimensionalities, including neutrons, trapped ions and single photons, but no experiment addressing all three loopholes has been performed in the qutrit scenario where entanglement cannot play a role. Demonstrating state-dependent contextuality of a solid-state system is also an important conceptual ingredient for universal quantum computation in surface-code architectures, currently the most promising route to scalable quantum computing.

Using our experimental platform developed for testing state-dependent contextuality, we plan to perform other tests of quantum contextuality including the state-independent test. In addition, our platform can be used for realization of the certified quantum random number generator operating in a three-dimensional Hilbert space. Quantum number generator based on superconducting quantum devices will allow for larger repetition rates (up to a few kHz), orders of magnitude faster than previous reported experimental realization of value-indefiniteness certified quantum random number generator.

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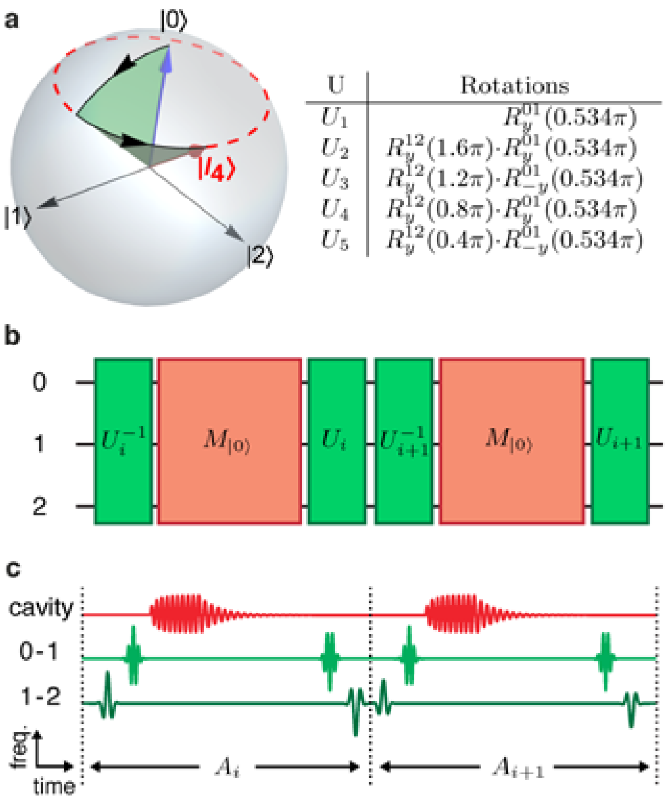

U	Rotations
U_1	$R_y^{01}(0.534\pi)$
U_2	$R_y^{12}(1.6\pi)\cdot R_y^{01}(0.534\pi)$
U_3	$R_y^{12}(1.2\pi)\cdot R_{-y}^{01}(0.534\pi)$
U_4	$R_y^{12}(0.8\pi)\cdot R_y^{01}(0.534\pi)$
U_5	$R_y^{12}(0.4\pi)\cdot R_{-y}^{01}(0.534\pi)$

Measurement protocol to test contextuality with superconducting qutrit: a. Unitary transformations U_i of the qutrit ground state to one of the target states used in the test. Each unitary can be decomposed into one or two rotations in the qutrit subspace. The trajectory of the state under transformation one of unitary transformation is shown as an example. b. The measurement protocol includes two sequential projecting binary measurements onto the ground state with unitary transformations before and after each measurement. The unitaries rotate the measurement axis into one of the protocol measurement directions. c. The actual experimental sequence for each pair of measurements. Measurement is implemented with a cavity probe signal and the qutrit rotations are constructed with microwave pulses applied at the qutrit transition frequencies.

Quantum optomechanics

Warwick Bowen (CI), Lars Madsen, Michael Vanner, Robin Cole, Eoin Sheridan, David McAuslan, Kiran Khosla, Glen Harris, George Brawley, Michael Taylor, Sarah Yu, James Bennett, Andrew Doherty (CI), Gerard Milburn (CI), Halina Rubinsztein-Dunlop (CI), Mark Baker, Tyler Neely, Yauhen Sachkou, Xin He, Stefan Forstner, Ulrich Hoff, Victor Jimenez, Chris Baker, Muhammed Waleed, Nicolas Mauranyapin, Beibei Li, Sahar Basiri
Collaborators: Ulrik Andersen, Hans Bachor, Jong H. Chow, Malcolm B. Gray, Jiri Janousek, Vincent Daria, Boris Hage, Francesca Iacopi, Aashish Clerk, Atieh R. Kermany, Neeraj Mishra, Ulrich B. Hoff, Hugo Kerdoncuff, Mikael Lassen, Bo M. Nielsen, Mankei Tsang, Shan Zheng Ang, Anja Boisen, Silvan Schmid

In quantum optomechanics, optical fields are used to control and manipulate the quantum behaviour of a micro- or nano-mechanical oscillator. Such research has prospects for not only fundamental tests of quantum mechanics at size scales inaccessible to other approaches, but allow applications in precision sensing, metrology and information technology.

In EQuS, we have a breadth of research in this area, spanning fundamental questions associated with how quantum systems decoherence, to new approaches using superfluid systems and atomic ensembles, and the use of quantum correlated light to improve measurement precision. We have made substantial progress in 2015, including the first demonstration of laser cooling of a liquid, facilitated by confinement of a superfluid helium film on a microscale optical cavity, the first direct measurements of thermal motion of a superfluid, the first use of photoconvective forces to actuate and cool a micromechanical system, and conditioning of non-Gaussian – though classical – states of a mechanical oscillator via nonlinear measurement.

Our researchers have also been involved in developing new techniques to trap and observe microparticles with orders-of-magnitude improved performance, in work funded by the United States Air Force Office of Scientific Research. We have also written the first review of applications of quantum metrology in biology, an area of increasing relevance for real world applications of quantum techniques, and the first textbook in the area of quantum optomechanics.

READ MORE

WE HAVE MADE SUBSTANTIAL PROGRESS IN 2015, INCLUDING THE FIRST DEMONSTRATION OF LASER COOLING OF A LIQUID, FACILITATED BY CONFINEMENT OF A SUPERFLUID HELIUM FILM ON A MICROSCALE OPTICAL CAVITY

Coulomb blockade and dual Josephson effects in nano-structured, superconducting 1D junction chains and SQUID arrays

Timothy Duty (CI), Ian McCulloch (CI), Karin Cedergren, Sergey Kafanov
Collaborators: Yuri Pashkin (Lancaster), Jared Cole (RMIT)

Arrays of nano-structured Josephson junctions are a potential platform for engineering novel quantum phases of matter. In addition, 1D arrays could support quantum versions of solitons—extended excitations that carry topological charge. Many concepts underlying the physics of such devices are shared with lattice systems of ultra-cold atoms or trapped ions. There are very significant features, however, that distinguish superconducting devices as quantum emulators from their atomic counterparts. Junction arrays exhibit strong-coupling and long-range interactions, and due to their “mesoscopic” nature, involve much smaller energy scales—-on the order of microwave photons. Experiments therefore must be carried out at millikelvin temperatures.

One important application of 1D chains of small Josephson junctions stems from the possibility of using these to implement the so-called “dual” Josephson effect. The usual Josephson effect occurs between two superconductors separated by a thin insulating barrier. A current through such structure is able to flow with zero voltage drop, in other words, with absolutely zero losses. This “supercurrent" arises from the coherent tunnelling of 2e-quantised charges (Cooper-pairs of electrons) through the barrier. Due to the Josephson effect, small superconducting circuits can be made to act as “artificial atoms”, and as such are strong contenders for a scalable quantum information processing technology. The Josephson effect also enables the technology behind the most sensitive magnetometers, which are based on SQUIDs (superconducting quantum interference devices).

In a superconductor, magnetic flux is forced to take on quantised values, integer multiples of the so-called magnetic flux-quantum, which equals h/2e. This begs the question: can one create alternative superconducting devices that operate on coherent tunnelling of magnetic flux-quanta, rather than 2e charges? Such devices could offer many advantages and new possibilities for quantum sensing and metrological applications. Coherent tunnelling of flux quanta or “coherent quantum phase slips” as they are called, can be pictured as the underlying physics of the dual Josephson effect, which also is known as a type of Coulomb blockade of Cooper-pair tunnelling. During 2015, CI Duty’s laboratory at UNSW carried out extensive measurements aimed at understanding the dual Josephson effect in both simple junction chains, and 1D SQUID arrays. By measuring dozens of devices, CI Duty’s group has discovered a universal scaling of the voltage threshold in these devices, which appears to be key to understanding the dual Josephson effect.

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Credit: EQuS researcher Dr Tyler Neely

QUANTUM MEASUREMENT AND CONTROL

RESEARCH ACTIVITY PLAN 2016

In 2016, CI Bowen's group will focus on three experimental efforts: 1) superfluid optomechanics in the quantum regime, 2) achieving the quantum regime in a room temperature millimeter scale optomechanical system, and 3) achieving strong coupling between the motional state of an ensemble of cold atoms and a micromechanical oscillator.

Superfluid optomechanics. The group's modeling suggests that the quantum regime of optomechanics, where quantum measurement backaction occurs at a faster rate than decoherence and can be used to control the quantum state of the mechanical element, is obtainable via their approach to superfluid optomechanics, where a nanoscale superfluid film is confined by van der Waal's forces to the surface of a microscale ultrahigh quality optical cavity. CI Bowen's group will seek to achieve this regime, which will allow the first demonstration of ground state cooling of excitations in a superfluid. The researchers will further investigate both theoretically and experimentally whether the presence of quantized vortices in a two dimensional superfluid can be used to couple to and control the quantum behaviour of phonon excitations in the fluid, and whether the exceptionally strong Duffing nonlinearities in single-atom monolayers of superfluid helium can be utilised to produce non-classical states.

Quantum optomechanics at room temperature and macroscale. It is believed that to observe quantum behaviour in a mechanical oscillator requires cryogenic conditions and high frequency mechanical motion. However, when utilizing a low frequency mechanical oscillator an advantage comes about due to the low rate of coupling of environmental perturbations from the momentum of the oscillator to the position. CI Bowen's group aims to use this advantage to achieve the quantum regime in millimeter-scale, kilohertz frequency mechanical oscillators at room temperature. These devices will be readout optically using the evanescent field of an ultrahigh quality whispering gallery mode resonator.

Atom-optomechanics: In collaboration, the groups of CIs Bowen and Rubinsztein-Dunlop have now developed an atom trap architecture based on an ensemble of atoms trapped around a tapered optical fiber. In 2016, they aim to use this as both a single atom detector, and to hybridize the collective motion of trapped atoms with the motion of a mechanical oscillator.

CIs Flammia, Doherty and Bartlett's research in the program on Controlling Quantum Systems has opened many new directions in the study of randomized benchmarking as a tool for characterizing the performance of engineered quantum systems. In the coming year, they aim to develop benchmarking procedures that can extract more detailed information about experimental devices than just the average noise level. It is clear from their theoretical work that information about whether noise processes are coherent or incoherent, and the spectrum of the noise, can be extracted from experiments. They will work with experimental groups to demonstrate these capabilities in practice.

CI Duty's lab will augment measurements on 1D junction and SQUID chains to include radio-frequency (RF) methods. This will enable so-called 'quantum capacitance' sensing of these chains in the insulating state (in other words, measurements of the charge compressibility). CI Duty's laboratory will extend its nano-fabrication technology in order to produce uniform arrays having several thousands of Josephson junctions, and to create 2D systems based on square, triangular and hexagonal lattices. CI Duty's group will use 1D junction arrays and RF methods to implement dual Josephson devices for quantum sensing of charge and flux.

CI Duty has recently initiated a collaboration with Chalmers University of Technology in Sweden aimed at exploring dual Josephson effects in 1D free-standing mesa's of bismuth strontium calcium copper oxide. This material is a high temperature superconductor, and therefore can operate at relatively high liquid nitrogen temperatures. Such structures can be considered as a stack of "intrinsic" Josephson junctions, with high uniformity in addition to a very long-ranged Coulomb interaction. Devices will be produced at Chalmers and measured in CI Duty's laboratory at UNSW.

CI Molina-Terriza's group will identify the quantum photonic states and the structures which are more suitable to perform the quantum processing of light at the nanoscale. They will also identify which quantum plasmonic states are the most relevant for sensing applications and use their techniques to control them. In 2016 CI Molina-Terriza's group will collaborate with the group of CI Volz in order to exploit the properties of this quantum plasmonic states to control the state of colour centres in nanodiamonds.

CI Tobar's group will investigate materials that have minimum influence on spins to limit the spin broadening, so to allow long spin and photon coherence times in quantum hybrid systems. Materials that can be used in both optical and microwave frequency domains are of interest for optical to microwave quantum transducers. Such materials include silicon, YSO and yttrium vanadate. Magnetic materials with lower optical losses than YIG are also under consideration.

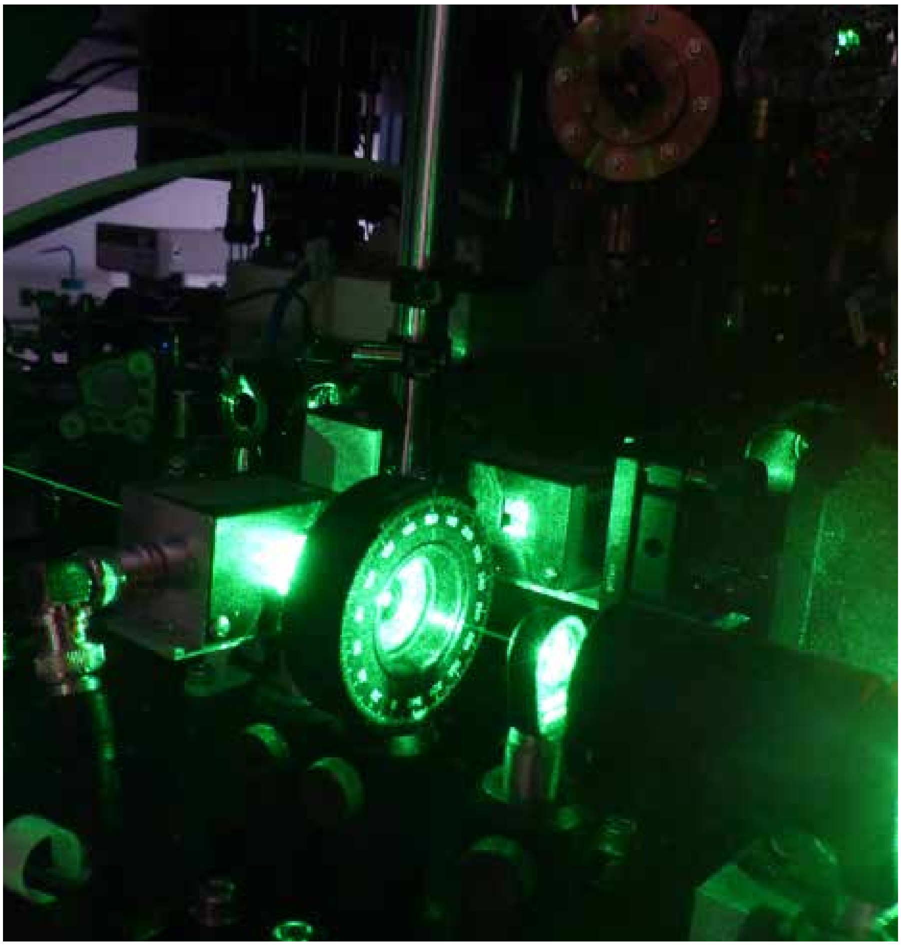
In the to hybrid high-Q acoustic oscillators and resonators project, CI Tobar's group will attempt to:

1. Couple the near quantum limited SQUID developed at Berkeley to the Quartz BAW resonator and read out modes near their quantum ground state. EQuS Research Fellow Dr Maxin Goryachev has won a $13,000 Research Collaboration Award travel grant to visit Berkeley to complete this work.
2. Progress towards coupling a transmon qubit by an intermediate LCR cavity to a Quartz BAW resonator, and allow ground state cooling.
3. Couple 3D LCR reentrant cavity to quartz BAW resonator.
4. Further investigate low noise read outs for the sapphire dumbbell project, for possible cryogenic operation.
5. Configure the above experiments to undertake tests on quantum mechanics of massive systems.

CI Stace will work with EQuS Research Fellow Dr Clemens Mueller to calculate the response of a driven microwave quantum dot coupled to both a cavity and a phonon bath. Anomalous gain has been observed experimentally in this system, and preliminary theory from others has partially explained this. They are developing a Keldysh diagrammatic approach to calculate the master equation, to systematically include all potential effects. They will work on a new design for superconducting circulators based on phase-slip junctions. Preliminary work on this has started to characterise the conditions under which this will work.

CI Stace, with CIs Brennen, Milburn and a new PhD student, has begun to work on relational time in anyonic systems.

In 2016, CD Milburn will continue to develop optomechanical schemes to place bounds on gravitational decoherence. In collaboration with Natalia Ares in Oxford he will work on a scheme, using capacitively coupled mechanical membranes in superconducting microwave cavities, to search for gravitational decoherence.
In collaboration with Tom Milburn at TU Wien, he will study an optomechanical Mach thermal clock. This provides a path to understanding the role of weak continuous measurement in fluctuation theorems for non-equilibrium systems. The role of quantum fluctuations in dynamical system with limit cycles will be studied, in collaboration with CI Stace, to elucidate quantum limits of thermal machines.



QUANTUM-ENABLED SENSORS AND METROLOGY

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TO DELIVER UNPRECEDENTED LEVELS OF SENSITIVITY AND PRECISION IN THE APPLICATION OF QUANTUM SYSTEMS IN SENSING, BIOMEDICAL IMAGING AND METROLOGY

CHIEF INVESTIGATORS

» Warwick Bowen
» Gavin Brennen
» Gabriel Molina-Terriza
» David Reilly
» Halina Rubinsztein-Dunlop
» Thomas Volz
» Andrew White

SNAPSHOT FOR 2015

1. Quantum metrology of optically active molecules
2. Nanodiamond trapping
3. Spins in solids – cooperative light scattering from nanodiamonds
4. Engineering quantum photonics
5. Nanodiamond MRI

Quantum metrology of optically active molecules

Gabriel Molina-Terriza (CI), Nora Tischler, Xavier Vidal
Collaborators: Mario Krenn, Anton Zeilinger

The promise of quantum metrology is to be able to achieve precision measurements even in situations when it is not possible to significantly increase the signal of your measurement device. One such situation is in the interaction of light with “delicate” objects, such as photosensitive biological objects or resonant molecules. In collaboration with the group of Professor Zeilinger in Vienna, we have given the first step to implement a quantum metrology scheme which is relevant to discern biological species: quantum metrology of optical rotatory dispersion. The measurement of optical rotatory dispersion in complex biomolecules allows to retrieve morphological information of certain radicals of the molecules. Our proof of principle experiment was performed with simpler molecules: simple sugars. This has allowed us to characterize this new technique.

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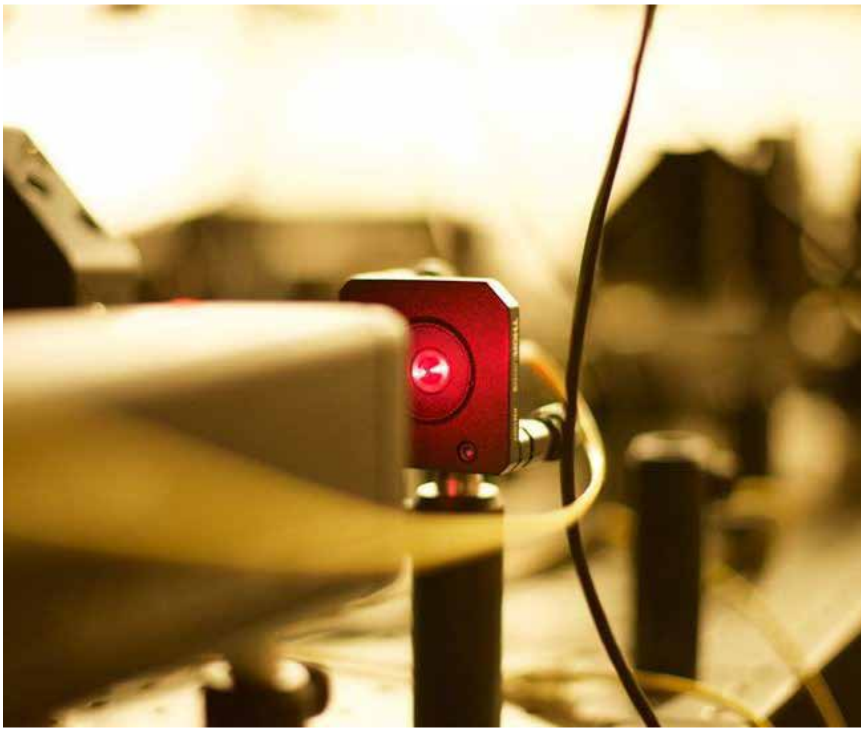

Credit: EQuS PhD student Christina Giarmatzi

WE HAVE GIVEN THE FIRST STEP TO IMPLEMENT A QUANTUM METROLOGY SCHEME WHICH IS RELEVANT TO DISCERN BIOLOGICAL SPECIES

Nanodiamond trapping

Thomas Volz (CI) , Gabriel Molina-Terriza (CI), Gavin Brennen (CI), Mathieu Juan, Carlo Bradac, Ben Besga

We completed a joint paper (arXiv:1511.04665) on the observation collectively enhanced dipole forces from optically trapped nanodiamonds (ND) after extending the underlying theoretical framework considerably. The paper presents measurements on NDs that are immersed in water and that are optically trapped by optical tweezers. Each ND is made of carbon atoms, but in addition contains a significant number of nitrogen-vacancy centres that act as artificial atoms with discrete atomic transitions. When tracking the motion of the individual NDs in the optical tweezers as a function of laser wavelength, we observe that the artificial atoms have a significant influence on the nanocrystal motion as a whole near the wavelength corresponding to their fundamental atomic transition. Near-resonant dipole forces are well-known from quantum gas experiments at ultra-low temperatures with well-isolated atoms. In contrast, our artificial atoms are embedded in nanocrystals which in turn are subject to a noisy, room-temperature environment. This leads to strong dephasing of the artificial atoms, and subsequently, a significant suppression of their coherent response to the trapping laser. Our theoretical analysis strongly suggests, that the detrimental effect of the environment is partially compensated by the collective interaction between the atoms. Such collective dipole forces have been predicted, but have never been seen in any system to date, not even in clean atomic systems. Our findings are interesting for emerging quantum technologies based on nanoparticle manipulation in particular in the field of quantum sensing.

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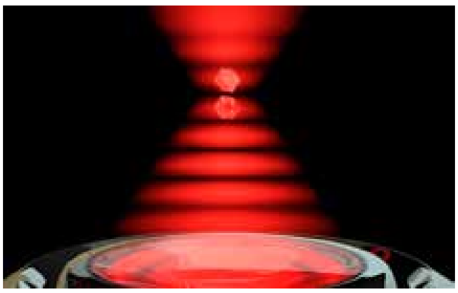
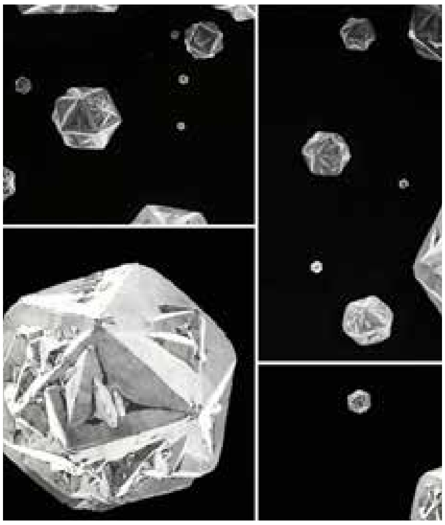


Credit: EQuS researcher Dr Mathieu Juan

Spins in Solids – cooperative light scattering from nanodiamonds

Thomas Volz (CI), Gavin Brennen (CI), Carlo Bradac, Mattias Johnson, Matt van Breugel, Rochelle Martin



Credit: EQuS PhD student Matthew van Breuzel. See @diamondnanosciencelab on Instagram

The nanodiamond trapping results suggest that collective/cooperative forces between the artificial atoms in the nanocrystals play an important role. This would imply that cooperative emission or superradiance should also be observable in high density NV nanodiamonds. However, there has been no report in literature to date – probably mainly because experiments have concentrated on the physics of individual centres and because the strong phonon sidebands of the NV centres suggest that cooperative emission might be strongly suppressed.

Motivated by the trapping results, we started a series of measurements on characterizing the ND material under off-resonant light scattering with ultrafast picosecond light pulses. We recorded time-resolved fluorescence from more than a hundred NDs, and it turned out that around 10% of the investigated NDs exhibited very fast decay, much faster than what is normally observed. A theoretical model that agrees very well with the experimental observations and that is based on collective (or Dicke) states suggests that subdomains of NV centres in the NDs interact cooperatively to give the observed lifetimes. An independent experiment revealed non-trivial correlations between photons emitted from the very fast NDs which again are nicely reproduced by our theoretical model. A manuscript is currently in preparation and will be submitted soon.

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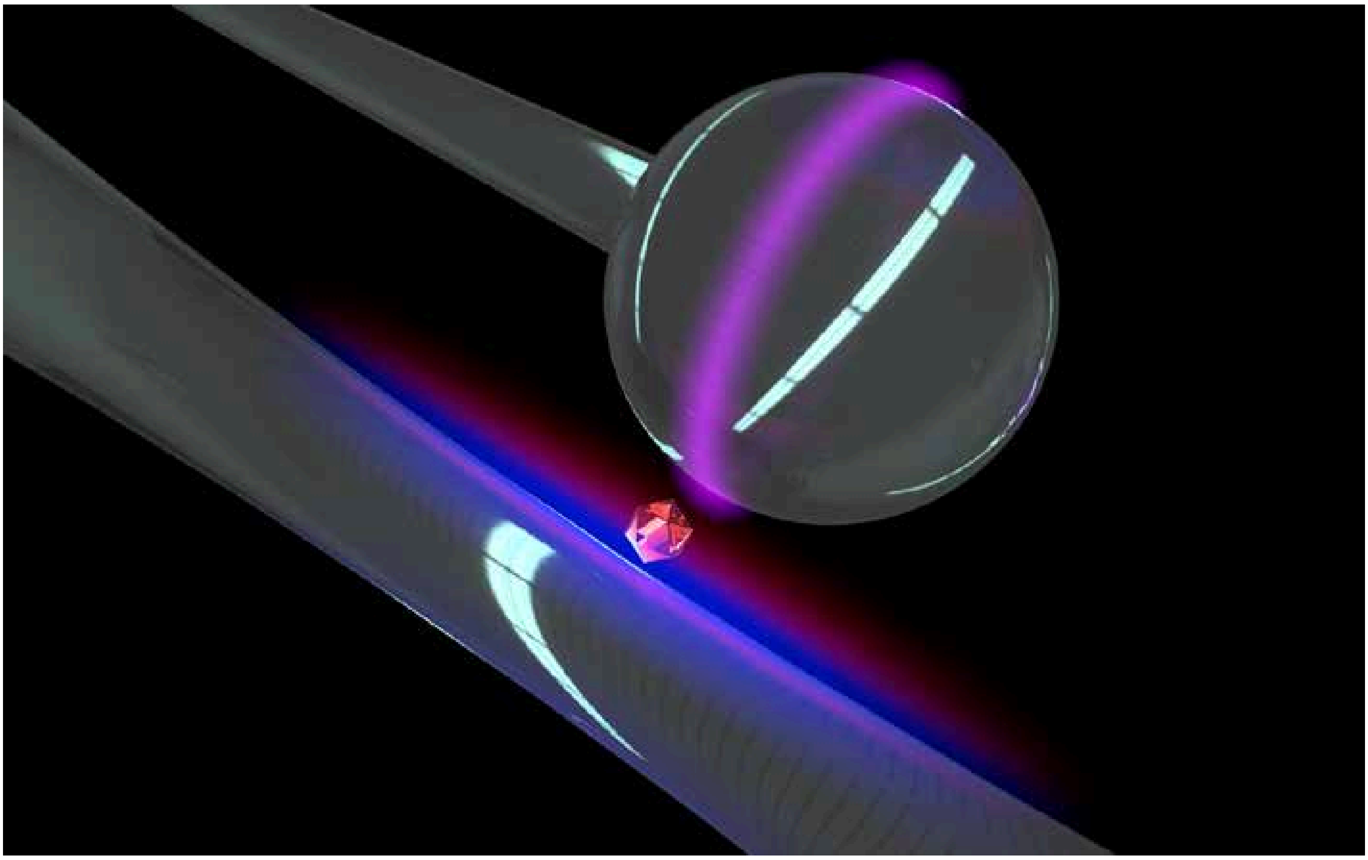

Credit: EQuS researcher Dr Mathieu Juan (Project Nanodiamond trapping)

Engineering quantum photonics

Andrew White (CI), Marcelo de Almeida, Devon Biggerstaff, Cyril Branciard, Benjamin Duffus, Alessandro Fedrizzi, Alexei Gilchrist, Geoffrey Gillett, Ivan Kassal, Sarah Lau, Juan Loredo, Aleksandrina Nikolova, Markus Rambach, Martin Ringbauer, Jacquiline Romero, Till Weinhold, Nor Azwa Zakaria, Aiden Zecevik
Collaborators: Carlos Anton, Alexia Auffeves, Matthew Broome, Jorge Casanova, Eric Cavalcanti, Guillaume Coppola, Michael Delanty, Justin Demory, Lorenzo De Santis, Roberto Di Candia, Olivier Gazzano, Valerian Giesz, Carmen Gomez, Markus Gräfe, Thomas Grange, Rene Heilmann, Gaston Hornecker, Daniel Lanzillotti Kimura, Loïc Lanco, Aristide Lemaitre, Graham Marshall, Thomas Meany, Kavan Modi, Stefan Nolte, Julen Pedernales, Simone Portalupi, Isabelle Sagnes, Pascale Senellart, Enrique Solano, Niccolo Somaschi, Michael Steel, Alexander Szameit, Michael Withford, Christopher Wood

Photonics, the technology that powers the global internet, uses bright lasers to function. Quantum photonics will allow currently impossible capabilities in not only communication, but in sensing, metrology, and even simulation, however it requires single particles of light—photons. The problem is that to date there have been only approximate single-photon sources: these are physically large and hard to multiplex—making 6 independent photons at a time currently occurs at a lower rate than gravitational-wave detection! In collaboration with Professor Pascale Senellart (France), we have cleared this decades-long roadblock away, developing a quantum-dot single photon source that is a million times smaller in volume, and 20 times brighter, than existing sources. The photons have near-ideal purity and indistinguishability, with visibilities up to 99.6±0.5% between the first and second consecutively emitted photons, dropping to 90% between the first and eleventh photons. Our demultiplexed source is orders-of-magnitude brighter than existing sources, allowing us to build a BosonSampling device—a quantum machine that cannot be efficiently simulated with a classical computer—that runs 100 times faster than previous implementations.

Scaling quantum photonics will also require a compact and phase-stable optical architecture. We have shown that femtosecond laser-written waveguides produce compact circuits with both high fidelity and excellent quantum interference, engineering—with Professor Mick Withford (Australia)—a quantum logic gate with process fidelities up to 93.1±0. 1%. Recent research into photosynthetic antenna complexes has shown evidence of quantum coherent energy transport, despite the noise of the cellular environment. Many theoretical studies—in photosynthesis or other nanoscale systems—have suggested that such environmental decoherence can significantly enhance the transport efficiency, an effect known as ENvironment-Assisted Quantum Transport, ENAQT. Despite its potential for improving transport in artificial quantum systems, it has so far never been directly observed. In collaboration with Professor Alex Szameit (Germany), we used an integrated photonic simulator to demonstrate the first implementation of ENAQT, showing noise can cleanly enhance transport efficiency.

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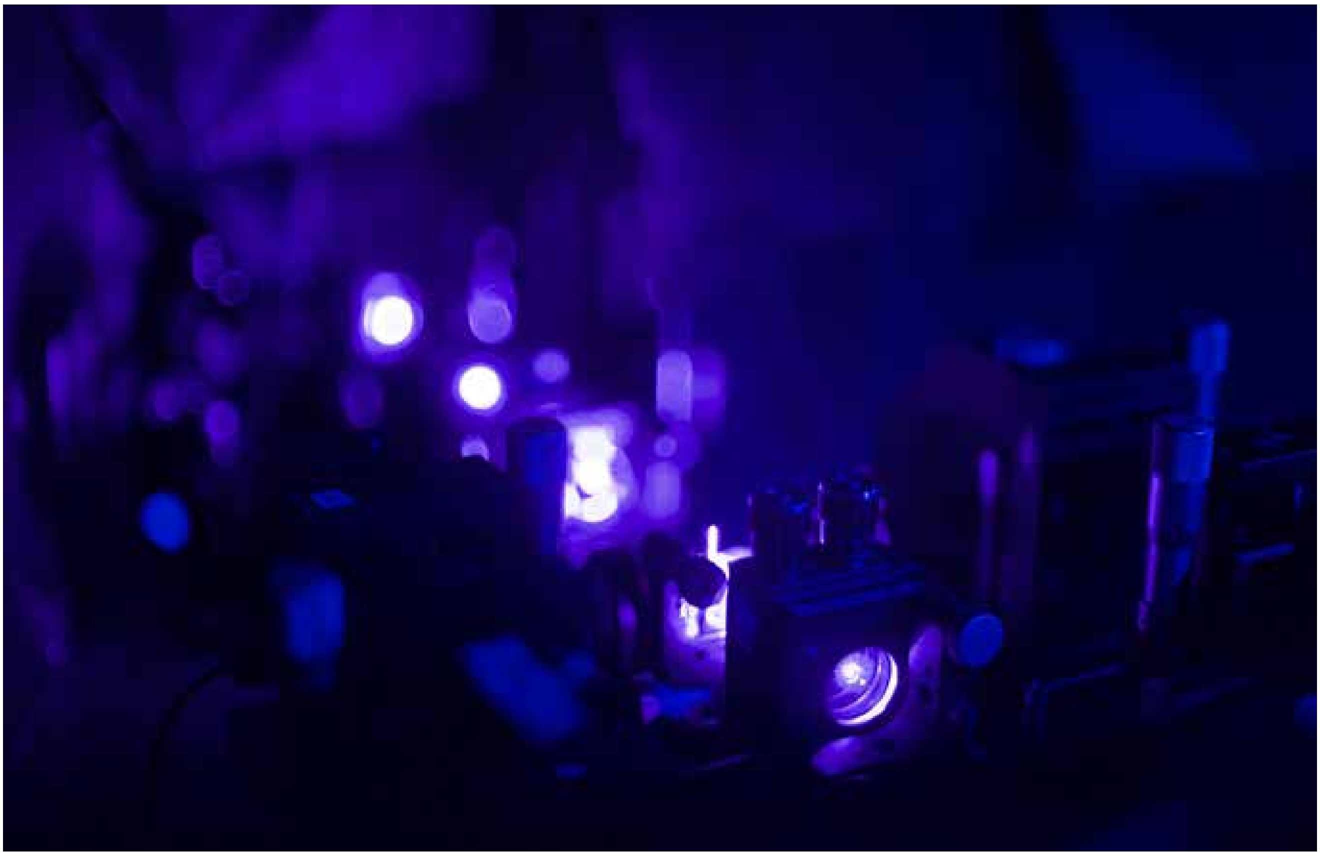
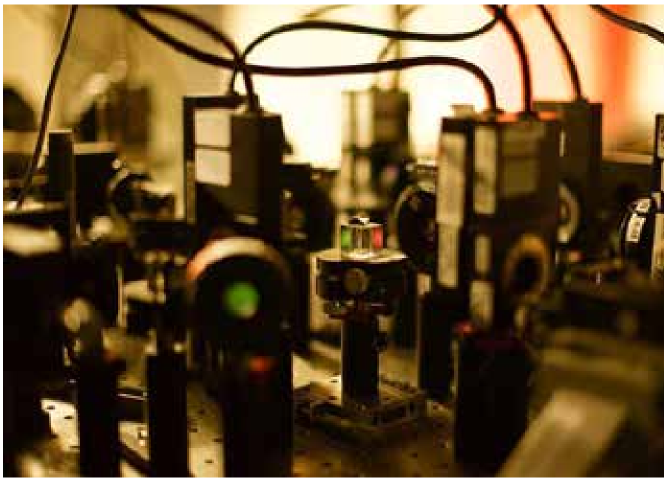


Nanodiamond MRI

David Reilly (CI), Torsten Gaebel, Ewa Rej, David Waddington, Thomas Boele, Andrew Doherty (CI), Stephen Bartlett (CI), Thomas Voltz (CI)
Collaborators: Matthew Rosen (Harvard / MGH)

In 2015, we successfully demonstrated the viability of hyperpolarized nanodiamond as a new MRI platform for the potential tracking and imaging of a range of diseases in vivo. The key breakthrough is to make nanodiamonds light-up in an MRI; only possible by aligning the spins of the carbon nuclei using microwave radiation at cryogenic temperatures. The microwaves drive electron spin flips and corresponding nuclear spin flops that lead to large nuclear polarizations. Nanodiamond has very long nuclear spin lifetimes, enabling the polarization to last for hours – plenty of time to take an MRI. This work was published in *Nature Communications*. In parallel, we have undertaken work to extend the coherence time of nuclear spins in nanodiamond, including examining the effect of nuclear polarization on the spin dynamics of the bath.



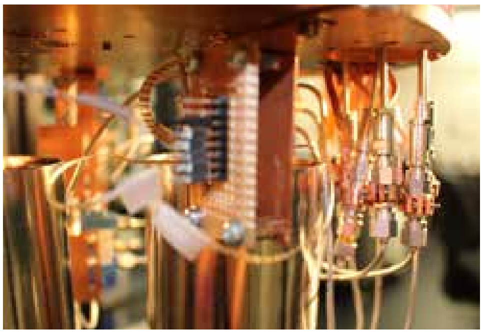
Credit: EQuS PhD student Christina Giarmatzi

OUR FINDINGS REVEAL HOW A NANOSCALE, SYNTHETIC VERSION OF DIAMONDS CAN LIGHT UP EARLY STAGE CANCERS IN MRI SCANS

Credit: Quantum Nanoscience Lab, USYD

QUANTUM-ENABLED SENSORS AND METROLOGY

RESEARCH ACTIVITY PLAN 2016



With microscopic potentials in place, CI Rubinsztein-Dunlop's group is investigating the transport of atoms in a coupled reservoir system. This system provides an ideal test bed for understanding the dynamics of superfluid transport in a controllable geometry for a variety of forcing conditions. The group plans to extend these initial investigations to the regime of active transport, in an implementation of an atomtronic device known as a quantum pump. Additional studies will involve studying the dynamics of coupled atomic reservoirs prepared with different thermodynamic properties, such as number and temperature.

Secondly, they are implementing an atomic-density-corrected feed-forward technique, which will allow the group to microscopically pattern optical lattices with spacing approaching 1.5 um. This should allow the group to demonstrate coupling between adjacent lattice sites, in a step towards studying the physics of configurable optical lattices.

Finally, the group plan to use large-scale ring traps for investigations of superfluidity, including the growth of coherence during the BEC phase transition, and in studying the breakdown of superfluidity and creation of quantized vortices. Such fluid dynamics will be important for the technical applications of superfluids in the emerging field of atomtronics, where circuit elements and sensors run on atomic superfluid currents.

CIs Molina-Terriza, Brennen and Volz plan to demonstrate optical trapping of ND crystals containing a large number of silicon vacancy centres. These have a stronger dipole moments, few phonon sidebands and can be packed more densely into the crystal. This should result in much stronger optical forces. The goal is to demonstrate a regime in which the atomic dipole forces dominate.

CI Volz and CI Brennen, with a new Masters student, will work on modelling superradiance effects in nanocrystals including dipole-dipole interactions. In addition, the researchers will be looking in more detail at time-resolved photon correlations in the context of superradiance.

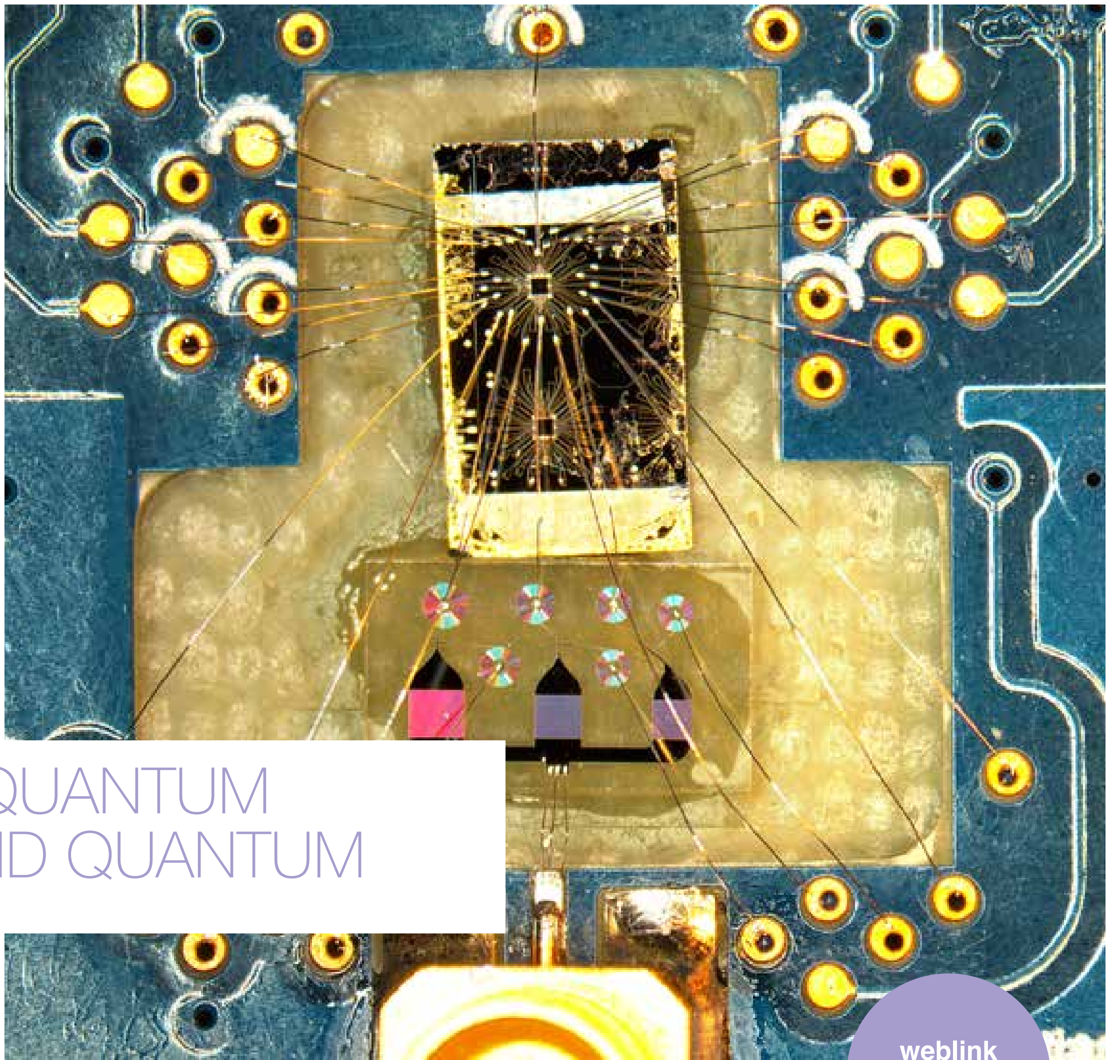
The team will also push the current experiments on ND levitation further. In particular, the plan is still to demonstrate Doppler cooling of a levitated ND with colour centres.

CI Volz and his team will make more extensive studies on superradiance in nanodiamonds, containing both NV and SiV centres. The researchers will characterize superradiance over a large temperature range down to a few Kelvin, making use of the closed-cycle cryostat in the Nanodiamond lab at Macquarie University.

CI Volz was awarded two internal grants (RIBG and MQSIS) from Macquarie University to fund a picosecond white-light source and an ultrafast streak camera which will both be central to the future experiments.

In 2016, CI Volz and his team will perform the long-planned single-spin measurements in ultrasmall nanodiamonds. In particular, they will carry out a systematic study of spin-coherence times in NDs as a function of size. The measurements will rely on a size-shrinking technique previously invented in the ND lab. In addition, coherence properties of high-density NV NDs will be studied, in light of planned experiments coupling NVs to superconducting flux qubits.

Credit: EQuS PhD student Christina Giarmatzi



SYNTHETIC QUANTUM SYSTEMS AND QUANTUM SIMULATION

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PRODUCING NOVEL STATES OF LIGHT AND MATTER EXHIBITING STRONG QUANTUM MECHANICAL CORRELATIONS WHICH WILL ENABLE SIMULATIONS OF COMPLEX INTERACTING QUANTUM SYSTEMS.

CHIEF INVESTIGATORS

» Stephen Bartlett
» Andrew Doherty
» Tim Duty
» Steven Flammia
» Alexei Gilchrist
» Ian McCulloch
» Gabriel Molina-Terriza
» Halina Rubinsztein-Dunlop
» Jason Twamley

SNAPSHOT FOR 2015

1. Simple controlled quantum systems
2. Tensor network simulations
3. Hybrid quantum systems
4. Quantum emulation of gravitational waves
5. Quantum matter
6. UQ Bose-Einstein condensation
7. Quantum simulations of quantum field theory

Simple controlled quantum systems

Alexei Gilchrist (CI), Peter Rohde, Keith Motes, Thomas Guff

An interesting question in quantum information science is where does the advantage in quantum algorithms actually come from? One avenue in which to look for insights is to study the simplest controlled quantum systems that can lead to a device that cannot be simulated with classical resources. Boson Sampling is one such architecture.

Outcomes included:

1. Extensions to other states of light: The original proposal for Boson Sampling used single photons as input, passive linear optical elements and single photon detection. Extensions to Boson Sampling to other states of light to gain physical insights to the origins of the complexity resulted in four publications in 2015 and a book chapter.

2. Fibre-loop implementation: In the course of investigating how to best implement Boson Sampling, we developed a scheme making use of temporal encoding using single fibre-loop that can be extended to more general information processing and to improving photonic sources.

3. Metrology: The Boson Sampling passive inteferometric structure also inspired a scheme that fed with only uncorrelated, single-photon inputs, coupled with simple, single-mode, disjoint photodetection, is capable of significantly beating the shot-noise limit.

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Tensor network simulations

Ian McCulloch (CI), Seyed Saadatmand, Jason Pillay, Stephen Bartlett (CI), Tim Duty (CI)

In 2015, significant progress was achieved along several fronts. CI McCulloch was appointed as an ARC Future Fellow, with a research program closely aligned with EQuS. Our investigations of topological properties of spin systems continued, with an elaboration of the phase diagram of the J1-J2 Heisenberg model on the Kagome lattice, investigating the magnetically ordered phases that surround the spin liquid region. The spin liquid region is a topological state that has unbroken SU(2) symmetry and appears to have a finite gap in the thermodynamic limit. PhD student Seyed Saadatmand published his first paper, on the properties of the triangular lattice Heisenberg model on a 3-leg ladder. Seyed has continued the study of this model, with work that is near completion showing that the 2D triangular lattice also has a spin liquid region, in the universality class of a Z2 spin liquid (this is the same topological order as Kitaev's Toric Code). This work is a breakthrough in the development of techniques, highlighting the relationship between projective representations of geometrical symmetries and topological order.

Ultracold atoms in an optical lattice form an ideal laboratory for Quantum Simulators. In particular, the recent development of techniques to synthesize artificial gauge fields opens the way to use neutral atoms to construct systems that mimic electromagnetic fields, and even non-Abelian gauge fields. In a collaboration involving researchers from Hannover and Munich, we have investigated with computational methods bosonic systems on 2-leg and 3-leg ladders in the presence of a synthetic magnetic flux, resulting in three publications in *Physical Review X, Physical Review Letters,* and *New Journal of Physics*. These systems turn out to have a rich phase diagram, including gapped and gapless Meissner phases (where flux is excluded from the bulk of the system, the same effect seen in superconductors), vortex lattices and vortex liquids.

The EQuS collaboration with CI Bartlett (USYD) is ongoing, with progress on the project of modelling ion-trap devices on a triangular lattice being substantially enhanced by the award of an EQuS Node Collaboration Grant. This will enable student Seyed Saadatmand to start work on this project, and it will provide funding for an Honours student to be co-supervised by CIs McCulloch and Bartlett.

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THIS WORK IS A BREAKTHROUGH IN THE DEVELOPMENT OF TECHNIQUES, HIGHLIGHTING THE RELATIONSHIP BETWEEN PROJECTIVE REPRESENTATIONS OF GEOMETRICAL SYMMETRIES AND TOPOLOGICAL ORDER

Hybrid quantum systems

Jason Twamley (CI)

Quantum Simulation of a Quantum Phase Transition

In the everyday world, we are all familiar with classical phase transitions when matter changes from one type of state to another, for example when solid water – ice – turns to liquid if we heat it. Researchers have been intrigued for decades by the quantum counterpart – or a quantum phase transition – where the quantum state of matter abruptly changes as you slowly change a quantity. Exploring quantum phase transitions experimentally has, until recently, been thought to be impossible as most theories predict that one requires very large light-matter coupling strengths – so high that experiments have so far been unable to reach them. This stumbling block was circumvented in our recent work with an international collaboration involving researchers in China, by developing a superconducting ship which is continually driven by microwave radiation. In our experiment we used a superconducting quantum chip containing four quantum bits (qubits), coupled to an integrated microwave superconducting cavity – essentially an electrical quantum superconducting circuit. By continually driving the electrical circuit and carefully measuring the quantum state of the qubits, the researchers were able to observe the abrupt change from a 'normal phase' to a 'superradiant phase', of the quantum chip as they swept through the quantum phase transition. This is one of the few experimental demonstrations of a quantum phase transition to date and was reported in *Nature Communications* in 2015.

Quantum Internet

Building a quantum internet is a key goal to permit long range quantum cryptography, communications, sensing and distributed quantum computation. Most of the advanced platforms for quantum computing are based upon superconducting quantum chips held near absolute zero in an ultra-cold dilution fridge. There is much effort around the world to develop methods to connect up superconducting quantum chips held in separate distant fridges – which would be the backbone of a long-distance quantum internet. The challenge is that superconducting chips use microwave quantum signals while long distance networking requires optical quantum signals. So far, almost all schemes proposed in the literature use moving parts (e.g. optomechanics), which is quite challenging experimentally. In recent work, Dr Xia and CI Twamley devised an all-solid-state interconversion scheme and modelled its operation in great length and detail based on recent experiments performed at NTT on coupling flux qubits to crystal diamond. Their theoretical protocol achieves very high fidelity networking between distant superconducting chips. This work was published in *Physical Review A*.

READ MORE

Quantum emulation of gravitational waves

Gabriel Molina-Terriza (CI), Ivan Fernandez-Corbaton, Mauro Cirio, Alexander Solano Buese

Quantum mechanics allows us to access a completely different realm of possibilities than classical mechanics allows. This means that, for example, particles such as photons can behave in a completely different manner than we could expect from our classical understanding of how light propagates. In this project, we have shown an extreme case of this possibility: by properly controlling the quantum state of pairs of photons, they can behave as the elusive gravitational waves. This opens up the possibility of implementing table-top experiments where one could experimentally emulate the generation, propagation and detection of gravitational waves. Our theoretical research shows the conditions necessary for such an experiment and the limitations of this approach.

READ MORE

Quantum matter

Stephen Bartlett (CI), Andrew Doherty (CI), Steven Flammia (CI), Aroon O'Brien, Simon Burton, Jacob Bridgeman, Chris Chubb, Sam Roberts, Alan Robertson, Henry Stoke, Cameron Duncan, Paul Webster
Collaborators: Andrew Darmawan, David Poulin (Sherbrooke), Dominic Williamson (Vienna), Tomas Jochym-O'Connor (Waterloo)

The Synthetic Quantum Systems program at the University of Sydney aims to address the key fundamental theoretical question: how can we create and harness quantum matter to process information in new ways?

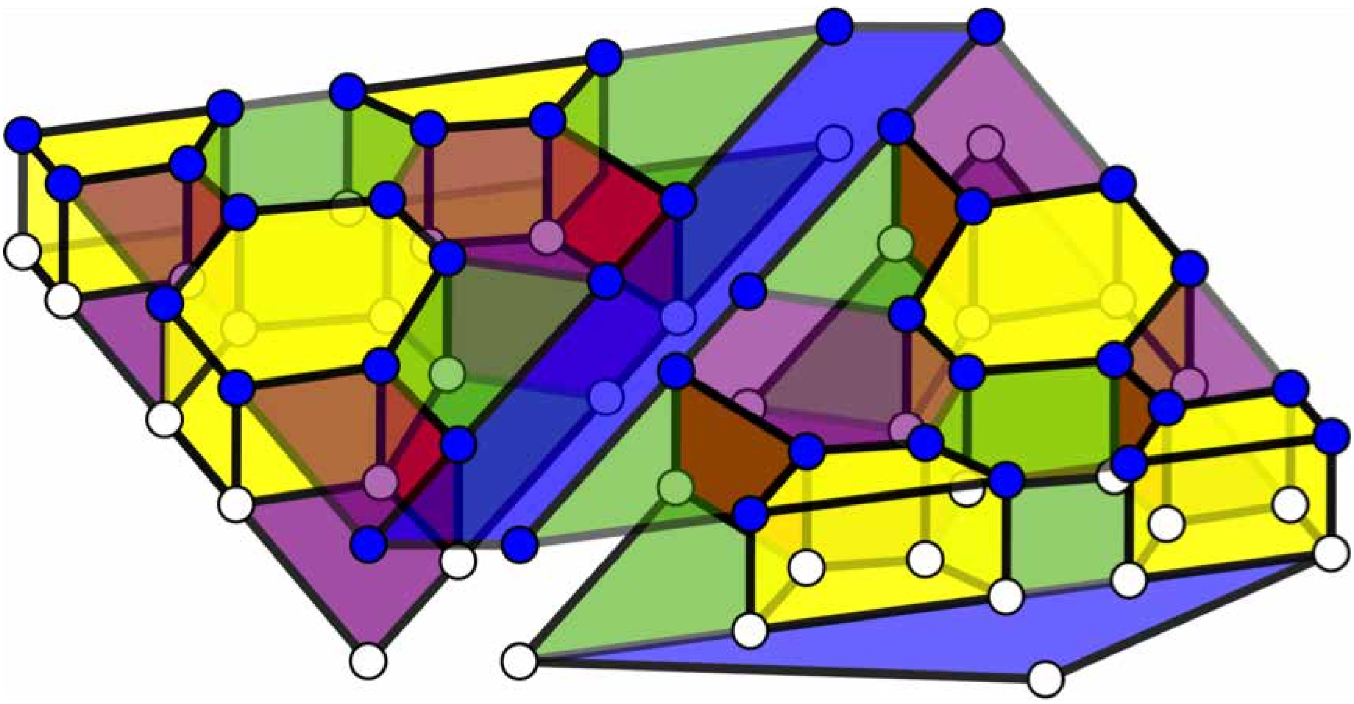
In 2015, we have built on advances made in the Synthetic Quantum Systems program in earlier years of the Centre to improve on currently known techniques for quantum error correction, and fault tolerant operations. Error correction allows for the storage of quantum information even in the presence of noise, while fault tolerant operations are procedures for processing information while simultaneously maintaining the effectiveness of error correction.

We have developed more efficient approaches to error correction for real devices dominated by a single noise process, such as dephasing. This will allow near-term devices with relatively small numbers of qubits to encode more information while still being robust to their dominant error processes. This work was in collaboration with David Poulin of the University of Sherbrooke.

In processing quantum information, it is important to have access to a universal set of operations so that any desired computation can be carried out. A breakthrough in the literature has been to realize that error correction procedures that are based on many-body quantum systems in three dimensions can be modified to allow for universal fault tolerant operations. This year we showed that it is possible to implement such an approach in a geometry where qubits can be arranged on a plane. The geometry is indicated in the figure and most operations that couple qubits involve only nearest neighbours. This is a major advantage for current chip-based approaches to quantum information processing such as superconducting or semiconductor qubits.

Finally, a third highlight for the year is that we have shown that it is possible to implement error correction procedures that are based on exotic hypothetical particles known as Fibonacci anyons. We developed the decoding procedures that make this possible as well as computer simulations that allow us to estimate how tolerant these procedures are to errors.

READ MORE



A 2D layout for error correction with fault tolerant implementation of a universal set of gates.

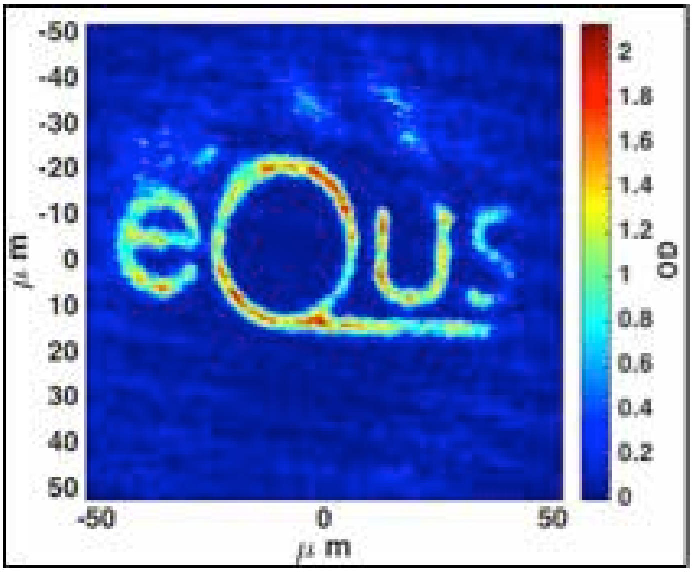
UQ Bose-Einstein condensation

Halina Rubinsztein-Dunlop (CI), Tyler Neely, Mark Baker, Guillaume Gauthier, Jake Glidden, Isaac Lenton, Severin Charpignon, Thomas Bell
Collaborators: Stuart Szigeti, Simon Haine, Matthew Davis, Michael Bromley

The last few weeks of 2014 saw the achievement of an 87Rb Bose-Einstein condensation on our newly built apparatus, by cooling an initial population of approximately one billion atoms to a temperature of 350 nK. In early 2015, we introduced a number of improvements to the apparatus, resulting in a 30-fold increase in the Bose-Einstein Condensate (BEC) to 5 million atoms, and increased the lifetime of the BEC 10-fold to 40 seconds by June.

In the second half of 2015, we implemented our high-resolution optical trapping and imaging system into the setup. We demonstrated the capability to microscopically pattern BECs with sub-micron resolution, and subsequently image the resulting BECs (see figure). This represents a major technical goal of the project, and the results have reproduced the design specifications.

READ MORE



Ultracold atoms confined to a microscopically patterned potential. Areas of high optical/atomic density (OD) are indicated in the figure.

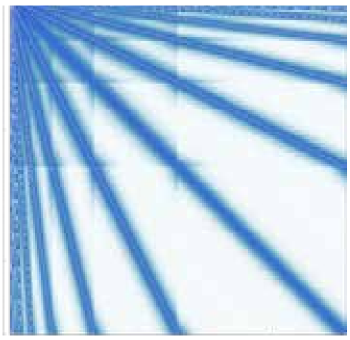
Quantum simulations of quantum field theory

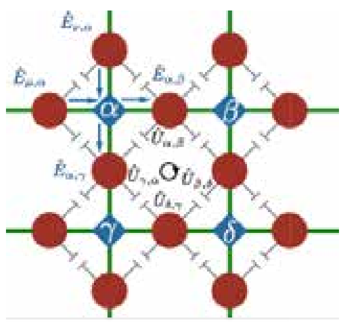
Gavin Brennen (CI), Tom Stace (CI), Sukwinder Singh
Collaborators: Guido Pupillo and Davide Vodola (Strasbourg), Enrique Rico (Bilbao), Barry Sanders (Calgary), Peter Rohde (UTS)

Quantum field theory (QFT) combines the physics of quantum mechanics and relativity, describing physics at very small sizes and high energies. A crowning achievement is quantum electrodynamics, which describes the interaction of light and charges alone and is the most accurate physical theory yet. A major application of classical computing power is in simulating QFT and lattice QFT has yielded remarkable successes in recent years, yet calculation of many quantities is out of reach. In 2015, CI Brennen's group proposed two new ways to perform quantum simulations of QFT which could overcome the computational hurdles, such as the notorious sign problem, that stymy classical calculations.

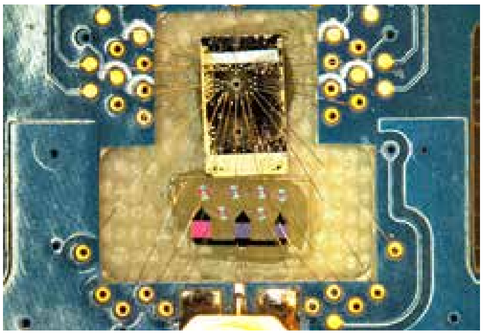
The first achievement was a methodology for simulating a type of theory named scalar bosonic QFT theory using a multiresolution wavelet basis. Wavelets are the basis of choice for a range of practical applications such as image compression since they provide a way to represent multiple scale features of data in a unified and efficient manner. Our encoding of a QFT allows one to zoom into various energy scales of a field theory, revealing both coarse features, which characterize the behaviour at critical points where the theory becomes scale invariant, and fine features to study scale dependent entanglement. The method proposed is quite versatile and can be engineered using a network of bosonic modes such as frequency/time encoded Gaussian states of light or using qubit arrays.

The second achievement was a proposal for simulating a U(1) lattice gauge field theory, which describes quantum electrodynamics, using superconducting fluxonium arrays. We showed how to engineer interactions between superconducting islands, each one encoding a multi-level system, in such a way that mimics the interactions between gauge fields on a lattice. In gauge theories, the relevant quantities to describe the physics are non-local order parameters which are extended strings of operators such as Wilson loops and 't Hooft strings. An important contribution we made was to provide a robust way to measure these operators in a non-demolition manner. Such measurements could be done with the assistance of a microwave cavity surrounding the fluxonium arrays and new physics, such as the dynamics after quech, could be probed using our mechanism. Furthermore, the use of fluxonium allows for tuning the number of levels that appear in the simulation which is akin to tuning the irreps that describe the theory, something that until now has not been feasible.





SYNTHETIC QUANTUM SYSTEMS AND QUANTUM SIMULATION



RESEARCH ACTIVITY PLAN 2016

CIs Doherty, Flammia and Bartlett's program on Quantum Matter will develop their recent results on quantum error correction and fault tolerant operations into detailed proposals for storing and manipulating quantum information in future experiments. In the final years of the Centre, they aim to bring the ideas about quantum information processing in synthetic quantum many-body systems to the point where they begin to have an impact on the experimental programs of researchers in engineered quantum systems.

CI Gilchrist will develop theoretical structures from quantum-information generalizations of classical thermodynamic ideas, such as resource theories and fluctuation relations, and apply them to far-from-classical quantum systems and devices. In 2015, Thomas Guff commenced a PhD at Macquarie University on this topic.

CI Molina-Terriza will look for the possibility of fabricating a material that can emulate the propagation of gravitational waves through a curved space-time. This is a trivial problem in relativity, but it will show the possibilities of his proposal. Further, he will study how to implement more complex systems, such as the interaction of gravitational waves with massive objects.

CI Twamley will return to an old topic of all-photonic quantum gates for propagating photons and seek to develop a Quantum Non-Demolition detection scheme. To date, there has been no scheme devised that can yield high fidelity quantum gates between single photons. All schemes using so-called cross-phase modulation so far proposed either introduce noise or yield very small phase shifts. He will study other methods to potentially overcome these difficulties. In addition, he will seek to improve on the solid-state quantum interface design. In 2015, he published a design that used an optical cavity as an essential ingredient and though feasible using fibre cavities, is technically challenging. Together with PI Jelezko, CI Twamley will develop a scheme that uses propagating optical modes in a superconducting-optical quantum interface. Using propagating modes and avoiding the use of an optical cavity makes the device easier to implement experimentally. Finally, he will explore applications of spins in diamond for quantum simulation and ultra-precise quantum sensing.

Within CI McCulloch's group, new postdoctoral fellow Dr Stuart Szigeti's work will focus on modeling Josephson Juncation Arrays, in collaboration with CI Duty (UNSW).

PhD student Seyed Saadatmand is in the final stages of a major study of the 2D triangular spin lattice, with work that will be presented at the 2016 APS March Meeting. Seyed will then join the collaboration with CI Bartlett on modelling ion trap devices, and will investigate the ground-state and dynamical properties of Ising spins in a triangular lattice in the presence of long-range interactions, which is a close representation of existing experimental devices. The ultimate aim of the project is to probe non-equilibrium effects and investigate the feasability of using this ion-trap setup as a quantum simulator.

PhD student Jason Pillay commenced in late 2015, and has started work on a collaboration with CI Stace, on the competition between the Kondo effect and RKKY interactions in a two-impurity system. They hope to understand the behaviour of quantum entanglement of interacting impurities at finite temperature.

CI McCulloch will continue the development of the Matrix Product Toolkit software for simulating quantum systems, with particular focus on detecting and analyzing topologically ordered states. A major project for 2016 is to develop computational techniques for investigating the dynamics of interacting anyons.

RESEARCH HIGHLIGHTS

QMC - QUANTUM MEASUREMENT & CONTROL
QESM - QUANTUM ENABLED SENSORS & METROLOGY
SQSQS - SYNTHETIC QUANTUM SYSTEMS & QUANTUM SENSORS

RESEARCH THEMES: QMC AND QESM

QUANTUM OPTOMECHANICS OF SUPERFLUID HE

The Bowen laboratory continues to exploit their discovery of strong optomechanical coupling between a superfluid He thin film and the whispering gallery modes of a toroidal cavity.

The paper: Laser cooling and control of excitations in superfluid helium by Glen Harris, David McAuslan, Eoin Sheridan, Yauhen Sachkou, Chris Baker, and Warwick Bowen

READ FULL PAPER

Abstract: Superfluidity is an emergent quantum phenomenon which arises due to strong interactions between elementary excitations in liquid helium. These excitations have been probed with great success using techniques such as neutron and light scattering. However, measurements to-date have been limited, quite generally, to average properties of bulk superfluid or the driven response far out of thermal equilibrium. Here, we use cavity optomechanics to probe the thermodynamics of superfluid excitations in real-time. Furthermore, strong light-matter interactions allow both laser cooling and amplification of the thermal motion. This provides a new tool to understand and control the microscopic behaviour of superfluids, including phonon-phonon interactions, quantised vortices and two-dimensional quantum phenomena such as the Berezinskii-Kosterlitz-Thouless transition. The third sound modes studied here also offer a pathway towards quantum optomechanics with thin superfluid films, including femtogram effective masses, high mechanical quality factors, strong phonon-phonon and phonon-vortex interactions, and self-assembly into complex geometries with sub-nanometre feature size.

RESEARCH THEMES: QMC AND QESM

OPTICALLY LEVITATED NANODIAMOND

The paper: Near-field Levitated Quantum Optomechanics with Nanodiamonds: Strong Single-Photon Coupling at Room Temperature by Mathieu Juan, Gabriel Molina-Terriza, Thomas Volz, and Oriol Romero-Isart

READ FULL PAPER

Abstract: We show that the dipole force of an ensemble of quantum emitters embedded in a dielectric nanosphere can be exploited to achieve a strong single-photon quantum optomechanical coupling, in the resolved sideband regime and at room temperature, with experimentally feasible parameters. The key ingredient is that the polarizability from an ensemble of embedded quantum emitters can be larger than the bulk polarizability of the sphere, thereby enabling the use of repulsive optical potentials and consequently the levitation at near-fields. This allows to boost the single-photon coupling by combining larger polarizability to mass ratio, larger field gradients, and smaller cavity volumes. A case study is done with a nanodiamond containing a high-density of silicon-vacancy color centres that is optically levitated in the evanescent field of a high-finesse microsphere cavity.

RESEARCH THEMES: QMC AND QESM

TRAPPING NANODIAMOND

The Volz lab demonstrated a new mechanism for optical trapping and levitation of diamond nanoparticles based on the cooperatively enhanced dipole forces from embedded NV centres.

The paper: Observation of cooperatively enhanced atomic dipole forces from NV centres in optically trapped nanodiamonds by Mathieu Juan, Carlo Bradac, Benjamin Besga, Gavin Brennen, Gabriel Molina-Terriza and Thomas Volz

READ FULL PAPER

Abstract: Since the early work by Ashkin in 1970, optical trapping has become one of the most powerful tools for manipulating small particles, such as micron sized beads or single atoms. The optical trapping mechanism is based on the interaction energy of a dipole and the electric field of the laser light. In atom trapping, the dominant contribution typically comes from the allowed optical transition closest to the laser wavelength, whereas for mesoscopic particles it is given by the bulk polarizability of the material. These two different regimes of optical trapping have coexisted for decades without any direct link, resulting in two very different contexts of applications: one being the trapping of small objects mainly in biological settings, the other one being dipole traps for individual neutral atoms in the field of quantum optics. Here we show that for nanoscale diamond crystals containing artificial atoms, so-called nitrogen vacancy (NV) color centres, both regimes of optical trapping can be observed at the same time even in a noisy liquid environment. For wavelengths in the vicinity of the zero-phonon line transition of the color centres, we observe a significant modification (10%) of the overall trapping strength. Most remarkably, our experimental findings suggest that owing to the large number of artificial atoms, collective effects greatly contribute to the observed trapping strength modification. Our approach adds the powerful atomic-physics toolbox to the field of nano-manipulation.

RESEARCH THEMES: QESM

QUANTUM ENABLED SENSORS

The Reilly laboratory achieved a high profile publication on their project to use hyper-polarised NV diamond as a means to enhance the sensitivity of MRI. This project has been an EQuS flag ship from the start and it is very satisfying to see it beginning to make an impact on our publications.

The paper: Hyper-polarized nanodiamond for NMR by Ewa Rej, Torsten Gaebel, Thomas Boele, David E.J. Waddington and David J. Reilly

READ FULL PAPER

Abstract: The use of hyperpolarized agents in magnetic resonance, such as 13C-labelled compounds, enables powerful new imaging and detection modalities that stem from a 10,000-fold boost in signal. A major challenge for the future of the hyperpolarization technique is the inherently short spin-relaxation times, typically <60 s for 13C liquid-state compounds, which limit the time that the signal remains boosted. Here we demonstrate that 1.1% natural abundance 13C spins in synthetic nanodiamond can be hyperpolarized at cryogenic and room temperature without the use of free radicals, and, owing to their solid-state environment, exhibit relaxation times exceeding 1 h. Combined with the already established applications of nanodiamonds in the life sciences as inexpensive fluorescent markers and non-cytotoxic substrates for gene and drug delivery, these results extend the theranostic capabilities of nanoscale diamonds into the domain of hyperpolarized magnetic resonance.

RESEARCH THEME: SQSQS

NEW PHYSICS FROM NEW TECHNOLOGY

The Fedorov lab, using the extraordinary quantum control and measurement efficiency afforded by superconducting circuits, demonstrated the best experimental demonstrating of quantum non-contextuality yet. This was based on implementing a set of five measurements on the non orthogonal states of a qutrit. The non-contextuality experiment is being prepared for submission.

The paper: Quantum contextuality with superconducting circuits.

READ FULL PAPER

Abstract: The ability to determine whether a multi-level quantum system is in a certain state while preserving quantum coherence between all orthogonal states is necessary to realize binary-outcome compatible measurements which are, in turn, a prerequisite for testing the contextuality of quantum mechanics. In this paper, we use a three-level superconducting system (a qutrit) coupled to a microwave cavity to explore different regimes of quantum measurement. In particular, we engineer the dispersive shifts of the cavity frequency to be identical for the first and second excited states of the qutrit which allows us to realize a strong projective binary-outcome measurement onto its ground state with a fidelity of 94.3%. Complemented with standard microwave control and low-noise parametric amplification, this scheme can be used to create sets of compatible measurements to reveal the contextual nature of superconducting circuits.

RESEARCH THEME: QMC

NEW PHYSICS FROM NEW TECHNOLOGY

On a similar foundational theme, the White group published experimental results that shed some light on a current debate that goes by the label “reality of the wavefunction”.

The paper: Measurements on the reality of the wavefunction by Martin Ringbauer, Ben Duffus, Cyril Branciard, Eric G. Cavalcanti, Andrew G. White and Alessandro Fedrizzi

READ FULL PAPER

Abstract: Quantum mechanics is an outstandingly successful description of nature, underpinning fields from biology through chemistry to physics. At its heart is the quantum wavefunction, the central tool for describing quantum systems. Yet it is still unclear what the wavefunction actually is: does it merely represent our limited knowledge of a system, or is it an element of reality? Recent no-go theorems argued that if there was any underlying reality to start with, the wavefunction must be real. However, that conclusion relied on debatable assumptions, without which a partial knowledge interpretation can be maintained to some extent. A different approach is to impose bounds on the degree to which knowledge interpretations can explain quantum phenomena, such as why we cannot perfectly distinguish non-orthogonal quantum states. Here we experimentally test this approach with single photons. We find that no knowledge interpretation can fully explain the indistinguishability of non-orthogonal quantum states in three and four dimensions. Assuming that some underlying reality exists, our results strengthen the view that the entire wavefunction should be real. The only alternative is to adopt more unorthodox concepts such as backwards-in-time causation, or to completely abandon any notion of objective reality.

RESEARCH THEME: SQSQS

SYNTHETIC QUANTUM SYSTEMS

The Duty group at UNSW achieved a significant result in their new research project in superconducting Josephson junction arrays. They showed that single-electron transport dominates deep in the insulating state of Josephson-junction arrays.

The paper: Parity effect and single-electron injection for Josephson-junction chains deep in the insulating state by Karin Cedergren, Sergey Kafanov, Jean-Loup Smirr, Jared Cole and Tim Duty

READ FULL PAPER

Abstract: We have made a systematic investigation of charge transport in 1D chains of Josephson junctions where the characteristic Josephson energy is much less than the single-island Cooper-pair charging energy, $E_J << E_{CP}$. Such chains are deep in the insulating state, where superconducting phase coherence across the chain is absent, and a voltage threshold for conduction is observed at the lowest temperatures. We find that Cooper-pair tunneling in such chains is completely suppressed. Instead, charge transport is dominated by tunnelling of single electrons, which is very sensitive to the presence of BCS quasiparticles on the superconducting islands of the chain. Consequently we observe a strong parity effect, where the threshold voltage vanishes sharply at a characteristic parity temperature T^*, which is significantly lower than the the critical temperature, T_c. A measurable and thermally-activated zero-bias conductance appears above T^*, with an activation energy equal to the superconducting gap, confirming the role of thermally-excited quasiparticles. Conduction below T^* and above the voltage threshold occurs via injection of single electrons/holes into the Cooper-pair insulator, forming a non-equilibrium steady state with a significantly enhanced effective temperature. Our results explicitly show that single-electron transport dominates deep in the insulating state of Josephson-junction arrays. This conduction process has mostly been ignored in previous studies of both superconducting junction arrays and granular superconducting films below the superconductor-insulator quantum phase transition.

INDUSTRY PARTNERS

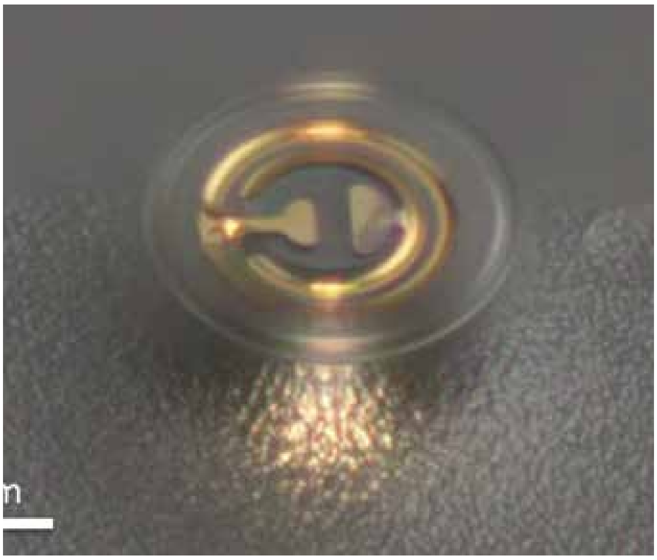
EQuS CHIEF INVESTIGATORS ARE WORLD EXPERTS IN QUANTUM SCIENCE AND ENGINEERING WITH STRONG TRACK RECORDS IN SCIENTIFIC DISCOVERY AND TECHNOLOGY DEVELOPMENT, LEADING TO INNOVATIVE COMMERCIAL APPLICATIONS AS EVIDENCED BY OUR INDUSTRY/PARTNER LINKAGES.

LOCKHEED MARTIN

Lockheed Martin is a global security and aerospace company which is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services. With a particular interest in next generation communications and sensing technologies that offer superior noise performance and/or increased robustness to environmental interference, Lockheed Martin has developed a strong partnership with researchers from EQuS.

CI Bowen's joint research with Lockheed Martin has strengthened this year. CI Bowen is collaborating with Lockheed Martin Deputy Chief Scientist Dr Luke Uribarri on silicon chip based devices that interface optomechanics with electronic circuits in an ARC Linkage Project. Such devices may enable precision on-chip clocks and radio-frequency receivers, as well as new technologies for robust electronics and communication systems.

This year, the team, including postdoc Dr Chris Baker and Tihan Bekker, have successfully developed the first ultrahigh quality optical microcavity with integrated electronic tuning (shown in the figure), allowing low power control of the optical resonance frequencies of the cavity with unprecedented speed. This work has been patented in Australia.



MOG LABORATORIES

MOG Laboratories (MOGLabs) is a start-up company which deals with research, development, and commercialisation of state-of-the-art electronics and lasers for basic and applied research, with a particular emphasis on quantum science. MOGLab customers pursue research in a range of areas, including cold atom and ion physics, quantum communication and computation, and ultraprecise atomic clocks.

MOGLabs works closely with EQuS to develop new products which commercialise ideas developed by Centre researchers.

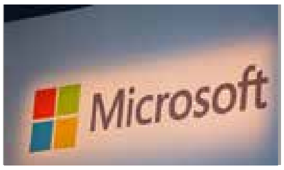
In 2015, MOGLabs and CI Biercuk were successfully awarded an ARC Linkage Project grant. The grant project aims to develop and commercialise optical cavity and frequency stabilisations technology to generate laser light at new and precise wavelengths. This project will help continue and develop Australia's leading role in quantum science.

NTT BASIC RESEARCH LABORATORIES, NTT CORPORATION

NTT Basic Research Laboratories in Japan conducts basic research in the fields of material science, physical science and optical science. More specifically of relevance to EQuS, it has research efforts in hybrid and superconducting quantum systems, quantum optics and photonics. NTT collaborates with EQuS researchers on research related to quantum technologies based on superconducting quantum devices and the modelling associated with that. In 2015, NTT and EQuS continued their joint research project on hybrid quantum systems for the realization of optical to microwave conversion.

NATIONAL INSTITUTE OF INFORMATICS (NII)

NII is Japan's only general academic research institution seeking to create future value in the new discipline of informatics. The National Institute of Informatics (NII) seeks to advance integrated research and development activities in information-related fields, including networking, software and content. These activities range from theoretical and methodological work through to applications. As an inter-university research institute, NII promotes the creation of a state-of-the-art academic-information infrastructure (the Cyber Science Infrastructure, or CSI) that is essential to research and education within the broader academic community, with a focus on partnerships and other joint efforts with universities and research institutions throughout Japan, as well as industries and civilian organizations. It has a research centre dedicated to quantum science and technology. NII and EQuS partnership seeks to conduct project based joint studies, as well as human resources development and to promote the utilization of its research results in society.



MICROSOFT RESEARCH

Microsoft Research is the research division of Microsoft and is one of the world's largest software research centres. Through Station Q Microsoft has developed a research group of world-class physicists, mathematics and engineers, including CI Reilly – a key participant in this international research endeavour.

END USER LINKS

19 BRIEFINGS

4 PATENTS

11 EDITORIAL BOARDS

12 ADVISORY BOARDS

EDUCATION & OUTREACH

WE ARE COMMITTED TO SHARING OUR RESEARCH WITH THE WIDER COMMUNITY. WE PROMOTE PUBLIC AWARENESS AND UNDERSTANDING OF QUANTUM PHYSICS BY MAKING IT FUN, INSPIRING AND ACCESSIBLE.

Scientists pave way for diamonds to trace early cancers

EQuS researchers have devised a way to use diamonds to identify cancerous tumours before they become life threatening.

Their findings, published in *Nature Communications*, reveal how a nanoscale, synthetic version of the precious gem can light up early-stage cancers in non-toxic, non-invasive Magnetic Resonance Imaging (MRI) scans.

Led by CI Reilly from the University of Sydney, researchers investigated how nanoscale diamonds could help identify cancers in their earliest stages.

"This is a great example of how quantum physics research tackles real-world problems, in this case opening the way for us to image and target cancers long before they become life-threatening," said CI Reilly.

The next stage of the team's work involves working with medical researchers to test the new technology on animals. Also on the horizon is research using scorpion venom to target brain tumours with MRI scanning.

Back to the future - talking with the White House

21 October 2015 marked the day Marty McFly and Doc Brown arrive in the fictional future of the iconic film *Back to the Future II*. CI White and EQuS PhD student Martin Ringbauer highlighted the event with a Google+ Hangout with the White House and a presentation (with costume) at the OSA Frontiers of Optics and Laser Science conference.

They answered a big question from popular movie *Back to the Future*. Namely, is time travel possible? Well, yes and no.

Einstein's theory of general relativity suggests the possibility of travelling backward through time using an Einstein-Rosen bridge, also known as a wormhole. EQuS researchers have used single particles of light to simulate the behaviour of quantum particles when travelling through time.

Einstein's work in special relativity showed us that travel forward in time is possible, but in general relativity, the equations show that you can go backward in time. The possibility in Einstein's equations has puzzled researchers for decades, as it creates paradoxes in the classical world like the "grandfather paradox."

To avoid this paradox, the research team simulated sending a quantum particle back through a closed time-like curve. They found that in quantum mechanics, when you send quantum particles back, you automatically avoid these grandfather paradoxes. This paradox is the exact problem Marty encounters in the movie when he almost prevents his parents from meeting. By changing the past, he could potentially erase his own existence and could have never set out for the time travel in the first place.

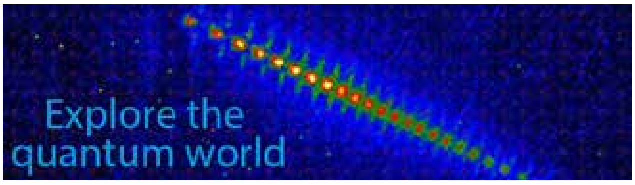
Our Quantum Future

Bringing together experts from academia and industry, on 22 October 2015 at the Sydney Museum of Applied Arts and Sciences (MAAS), a panel discussion and public Q&A was held to discuss the potential future applications of quantum science and technology.

Organised by CI Twamley supported by QSCITECH and EQuS, this event featured EQuS CIs Brennen and Molina-Terriza, Professor Jelezko (Ulm University), Professor Jonathan Dowling (Louisiana State University, USA), Dave Wecker (Microsoft), Luke Uribari (Lockheed Martin), Ray O Johnson (QxBranch), and chaired by Dr Cathy Foley (CSIRO).

The panel discussed the potential commercial, cultural and social ramifications of tomorrow's quantum technologies. The event was attended by high schools, the public, industry and government representatives and a lively question and answer session ensued.

Quantum Short Stories



EQuS joined with Singapore's Centre for Quantum Technologies in September 2015 to bring Quantum Shorts 2015 to life.

Sponsored by *Scientific American*, Quantum Shorts (shorts.quantumlah.org) sought short stories up to 1000 words long that draw inspiration from quantum physics. The competition is open to all aspiring science fiction writers with two award categories – open and high school.

Quantum haiku challenge

EQuS launched a mini-competition in support of Quantum Shorts which challenged students and adults around the world to describe the wonder of quantum physics in 17 syllables or less through haiku. Participants submitted up to three original poems which were shortlisted by EQuS. The winner received a one-year digital subscription to *Scientific American*.

The winning entry came from Igor Teper from the United States of America (see below). Igor won a one-year digital subscription to *Scientific American*.

SUPERPOSITION.
I'M IN TWO PLACES AT ONCE.
YOU ARE IN NEITHER.
- IGOR TEPER

The story that quantum physics tells about the world is so utterly strange, and yet more than a century of clever and beautiful experiments shows that it's also true. Quantum physics has fascinated Igor ever since he first learned about it, and is largely what drew him to a career as a physicist. Igor currently works at a company that develops sensors based on the quantum-mechanical properties of atoms - he likes to say that he teaches old atoms new tricks at temperatures near absolute zero. Igor is also a writer of fiction, poetry and science essays.

Highly commended

Wave function collapse—
the last cherry blossom lands
as she says I do.
- Stewart Baker

Observer, observed
A quantum dance of equals
Yet we disagree
- James Meyers

September evening:
Sunlight lingers on the lake
Neutrinos pass through
- Robert Dawson

Red breast's guide home,
Quantum entanglement, is it
something in the eyes?
- Samantha Renda

Quantum mechanics
Can only be understood
With uncertainty.
- Jeff Haas

Australian Museum's Eureka Award Winner

For contributions at the leading edge of quantum science research, CI Michael Biercuk was awarded the Macquarie University Eureka Prize for Outstanding Early Career Researcher in 2015.

For particular applications, quantum computers could be more powerful than any machine using current technology. However, functioning quantum computers may still be a decade away. CI Biercuk is bringing some of those quantum benefits forward. He has:

- Reduced information loss from quantum information systems.
- Built a simulated quantum computer of 300 atoms, each storing one 'quantum bit' (quibit) of information, and smashing the 30–40 quibit threshold at which quantum simulators exceed the capabilities of current supercomputers.
- Set the record for the smallest force ever measured.

A particular quantum computing roadblock has been the systems' vulnerability, with even tiny environmental fluctuations corrupting the stored information. CI Biercuk and colleagues developed a method of error suppression that has been described as quantum computing's Rosetta Stone for the transformational effect it will have on the field.

Utilising quantum effects on trapped ions, CI Biercuk set the record for the smallest force ever measured: at the level of yoctoNewtons, or a million-million-billion times smaller than the force of a feather pressing down on a table. The technology has potential for mining exploration.

Using quantum simulation, he is also looking for the key to room-temperature superconductivity. Among other applications, this has the potential to eliminate the significant losses of transmitting electricity, which in Australia consumes 6 or 7 per cent of electricity generated.

Smashing fun with liquid nitrogen

In 2015, 10 students from the HSC Physics class at Mitchell High School, NSW visited our University of New South Wales node. Dr Karin Cedergren, a postdoctoral researcher, supervised the visit.

The students spent time in the Superconducting Nano-Devices Laboratory with Karin to learn about why we are interested in nano-scaled devices. Karin explained to the students that we are now reaching the physical limits for scaling down electronics while producing the same behaviour. In order to continue the rapid development in this field of the past few decades, researchers need to understand the behaviour of electronics on a scale where we can see the effect of individual electrons and their quantum nature. She also introduced the girls to why researchers need such low temperatures and how they cool objects.

Karin said, "I think it is important to show students early on that physics is one of the many possibilities for what they can do in the future."

"But perhaps more importantly today, when quantum physics has become essential in order to explain the properties of our frontier nanotechnology, it is important to show the young students that it is something real, and give him or her a glimpse of this fascinating field. If we, as researchers, don't reach out to the public and make our research comprehensible, we are partly to blame when the scientific terminology is misused as a means to explain various pseudoscientific beliefs that don't have any backup in science."

In a discussion on whether high school tours are an effective means of communicating science she added, "Certainly! It's inspiring to see how engaged some of the students are."

Getting involved in science communication

Samantha Hood is a postgraduate student at the University of Queensland currently undertaking her PhD with postdoctoral researcher Ivan Kassal. Her research looks at charge separation in organic solar cells using computational methods. Samantha hopes to establish a strong theoretical foundation to describe charge transport in organic solar cells, which will lead to experimental tests.

As well as undertaking her PhD within EQuS, Samantha is a member of the Science Demo Troupe at The University of Queensland. She joined the troupe in June 2015 because she was eager to get involved with a community of volunteers with a passion about science communication.

The Demo Troupe is a group of volunteer students devoted to spreading their enthusiasm for science. They meet regularly to practise demonstrations and visit schools to run science activities.

In 2015, several EQuS students joined the Demo Troupe for a number of events, including UQ Experience Science Week (July 21 and 22), National Aborigines and Islander Day Observance Committee (NAIDOC) Week (July 10) and Science Week. They performed for high school students, gave hands-on demonstrations for 3-12 year olds and held open workshops.

Samantha said, "My involvement with the Demo Troupe has increased my confidence in presenting in public and communicating science to a wide range of audiences, including young children at schools and festivals as well as prospective university students."

"I have gained skills in organising physicists, which is more difficult than I thought it would be!"

The Science Demo Troupe engages people with hands-on experiments and interesting science shows. They get the public excited about science. Samantha believes that part of their appeal is that, as young student volunteers, they are approachable.

"We are enthusiastic about sharing knowledge. We make science more accessible to young people, which I think is the most worthwhile way we can use our skills."

In 2016, the Demo Troupe will be supporting the World Science Festival in Brisbane with street exhibitions of science.

Ku-ring-gai High School teachers visit the Diamond Nanoscience Lab

As a small secondary school in Northern Sydney, Ku-ring-gai High School provides a personalised education experience to its students. Matthew van Breugel, EQuS PhD student at Macquarie University, hosted two teachers from Ku-ring-gai for a half-day introduction to quantum physics and a tour of the Diamond Nanoscience Laboratory.

Matthew took the teachers on a tour of the laboratory and discussed the basics of what his research group investigates, how they investigate and why.

Matthew said, “The teachers were very engaged and keen to have me out to the school later in the year. They were thrilled to learn about current research and excited to take information back to their classes.”

Work experience with the EQuS admin team

In 2015, EQuS hosted Emma Mumbler, a trainee from the UQ Indigenous Traineeship Program. The program involves a placement in the university with a component of the traineeship including the completion of a Certificate III in Business Administration.

Emma previously graduated from Abbotsleigh in NSW, Australia. She moved to Brisbane to undertake the traineeship at The University of Queensland. While at EQuS, Emma supported the administration team during the Winter School and Professional Development Workshop. She became our photographer during the events and also collected content for the new EQuS website.

Emma said, “I enjoyed my experience at EQuS. I learnt a lot, particularly when we launched the new website.”

Quantum Physics for Babies goes viral

It was during the 2015 EQuS Annual Workshop that EQuS postdoctoral researcher Chris Ferrie made a surprising discovery – his book “Quantum Physics for Babies” had been shared by Facebook founder Mark Zuckerberg.

The post attracted more than 650,000 likes, 14,000 shares and 17,000 comments.

Zuckerberg wrote, “My next book for A Year of Books is Quantum Physics for Babies!" the billionaire wrote. "Just kidding. It's actually World Order by Henry Kissinger ... I am loving reading to Max. Next year looks like it's going to be A Year of Children's Books!"

Speaking with the *Sydney Morning Herald*, Chris Ferrie said, “If you look at the picture close enough, I’m pretty sure she’s sleeping. I don’t know if that’s because of the book.”

Work experience in EQuS Diamond Nanoscience Lab

Nick Glasson, a year 10 student, was given the opportunity to work for a week in the Macquarie University Diamond Nanoscience Laboratory under the supervision of Dr Carlo Bradac and PhD student Matthew van Breugel.

An excerpt from his work experience report follows:

"Throughout the week, I gained a lot of practical experience in the lab, as well as learning a lot about nanodiamonds, optics and the importance of the research being performed, and its potentially exciting implications in a large number of different fields."

"Working in the lab was a fantastic experience, and I greatly enjoyed every day. Everything was explained really well, and I felt like I always understood the risks and how to use anything I needed to, and, if I had any questions, they were explained really well."

"I particularly enjoyed learning from Dr Carlo Bradac and Matt van Breugel about some of the physics behind NV centres, and learning why the potential applications are so exciting. I learnt a lot, and I’m very grateful to have been given the opportunity." READ MORE

Professional Development Workshop

EQuS offered professional training during 2015 to help staff and students with the tools to enhance their career.

To equip our Early Career Researchers with information and tools to further their career, we held a Professional Development Day on June 29 before the EQuS Winter School. The day included:

» Career planning with Dr Rowan Gilmore

» Commercialisation and intellectual property management with Dr Rowan Gilmore and Dr Howard Leemon

» Science communication with Associate Professor Joan Leach and Dr Maggie Hardy

» An interactive panel

In 2016, we will expand these initiatives with more opportunities designed specifically for Early Career Researchers and postgraduate students.

EQuS Winter School

We held a highly successful EQuS Winter School in July 2015 at The University of Queensland. EQuS CI Fedorov put together an exciting program for our students covering quantum measurement, quantum information and Bose-Einstein condensation.

The Winter School ran over four days with opportunities for networking and science communication seminars.

Fourth Annual Optomechanics Incubator Workshop

In December 2015, EQuS held our fourth annual Optomechanics Incubator Workshop at Customs House in Brisbane. The Incubator is a one-day workshop that brings together the local and international optomechanics research community to focus on important challenges in the field and grow collaborations.

Sydney Quantum Information Theory Workshop 2015

The annual workshop brings together Australian and international theorists to discuss and workshop new and unpublished research in theoretical aspects of quantum physics.

The 2015 workshop was the largest to date, with over 70 researchers presenting and discussing the latest developments in the connections between quantum information theory and many-body physics.

Our Fifth Annual EQuS Workshop

EQuS hosted its fifth Annual Workshop in December 2015 at the RACV Royal Pines Resort in Benowa, Queensland. 134 delegates representing Centre nodes, overseas collaborators and Advisory Board Members were present. The Workshop was broken into plenary sessions addressing key areas of EQuS research.

Highlights:

» The EQuS XPrize Competition (a collaborative activity which asked participants to create a grant submission in fifty minutes)
» International speakers, including Professor Alain Aspect, Professor Bill Munro, Professor Jörg Schmiedmayer, Professor Jack Harris and Professor Ian Walmsley
» Poster night (winners were PhD student Claire Edmunds and postdoctoral researcher Clemens Mueller. People's choice winners were PhD student Alice Mahoney and PhD student Ewa Rej with honourable mention to the EQuS Admin team)
» Morning Yoga classes led by PhD student Keith Motes and an EQuS pool competition

LIFE AFTER EQuS

Dr Alessandro Fedrizzi
Associate Professor Heriot-Watt University, UK

After seven years at UQ and in EQUS first as a postdoctoral and then as a DECRA fellow, Dr Alessandro Fedrizzi assumed a position as Associate Professor at Heriot-Watt University in Edinburgh in September 2015. Alessandro will continue to push the boundaries in photonic quantum technology, with a focus on ultrafast photonic cluster state generation for all-optical quantum networking. This research program is supported by a 5-year Quantum Technology Fellowship awarded by the UK Engineering and Physical Sciences Research Council (EPSRC).

Dr Matt Wardrop
Data scientist, Airbnb

After completing his theoretical thesis entitled "Quantum gates for quantum dots" in early September 2015, Dr Matthew Wardrop undertook a seven week postdoctoral training fellowship which helped him bridge the gap between academic and data science. He is now a Data Scientist at Airbnb.

Dr Michael Vanner
Senior Researcher, Oxford University, UK

Michael Vanner joined EQuS in 2013 as a UQ Postdoctoral Research Fellowship holder and worked within several groups on both experimental and theoretical quantum optics. Michael has recently moved to the University of Oxford as a faculty member and is starting a new quantum optomechanics program. His research is supported by the EPSRC and will explore the foundations of physics as well as develop new quantum technologies.

Dr Glen Harris
Researcher, Yale University, USA

After spending more than five years in the Queensland Quantum Optics Lab at the University of Queensland, Dr Glen Harris has started a new quantum optomechanics experiment at Yale University.

2015 GRADUATES

Congratulations to EQuS 2015 graduates

Romain Bara-Maillet, PhD
Sahar Basiri Esfahani, PhD
Devon Biggerstaff, PhD
Courtney Brell, PhD
James Colless, PhD
Bixuan Fan, PhD
Warrick Farr, PhD
Glen Harris, PhD
Devin Smith, PhD

Thomas Guff, Masters by Research
Daniel Lombardo, Masters by Research
Reece Roberts, Masters by Research
Jarrah Sastrawan, Masters by Research
Matthew van Bruegel, Masters by Research
Dominic Williamson, Masters by Research
Andrew Wood, Masters by Research

Matthew Allen, Honours
Cameron Duncan, Honours
Claire Edmunds, Honours
Aein Eskandari, Honours
Theodore Faros, Honours
William de Ferrenti, Honours
Saivan Hamama, Honours
Hakop Pashayan, Honours
Alan Robertson, Honours
Alistair Robertson-Milne, Honours
Harrison Steel, Honours
Henry Stoke, Honours

EQuS Workshop 2015 - PhD Students Samantha Hood, Christina Giarmatzi and Sarah Lau

EQuS Workshop 2015, Poster session

EQuS PERFORMANCE

THE HISTORY OF PHYSICS SHOWS THAT NEW DISCOVERIES FOLLOW NEW MEASUREMENT TECHNOLOGY. IN THE PAST FOUR AND A HALF YEARS, WE HAVE MADE SIGNIFICANT PROGRESS IN OUR RESEARCH

COLLABORATIONS

EQuS researchers collaborate with over **95** institutes in **19** countries

FELLOWS

3 Fellows of the Australian Academy of Science

6 Current ARC Future Fellows

RESEARCH OUTPUT

- 97 PUBLICATIONS
- 4 PATENTS
- 78 INVITED/KEYNOTE LECTURES
- 41 MEDIA COMMENTARIES

COMMUNICATION

- 34 PUBLIC LECTURES
- 803 FOLLOWERS SOCIAL MEDIA
- 4 NEWSLETTERS
- 10 WORKSHOPS

EQuS HAS ESTABLISHED A WORLD-LEADING RESEARCH COMMUNITY TO CATALYSE THE DEVELOPMENT OF QUANTUM TECHNOLOGIES AND DEVELOP A COMPREHENSIVE FRAMEWORK FOR TRAINING AND MENTORING A NEW GENERATION OF SCIENTISTS AND ENGINEERS

RESEARCH TRAINING

EQuS is committed to developing, training and mentoring students and researchers. In 2015, we delivered a number of professional development initiatives that covered grant writing, science communications, career pathways and development and Intellectual Property

GOVERNANCE

The EQuS board met twice in 2015.

They provide direction on research strategies, public relations strategies, communications, and translation of knowledge into outcomes with representatives of each Partner Institution and influential people from business and government sectors.

LEARNING

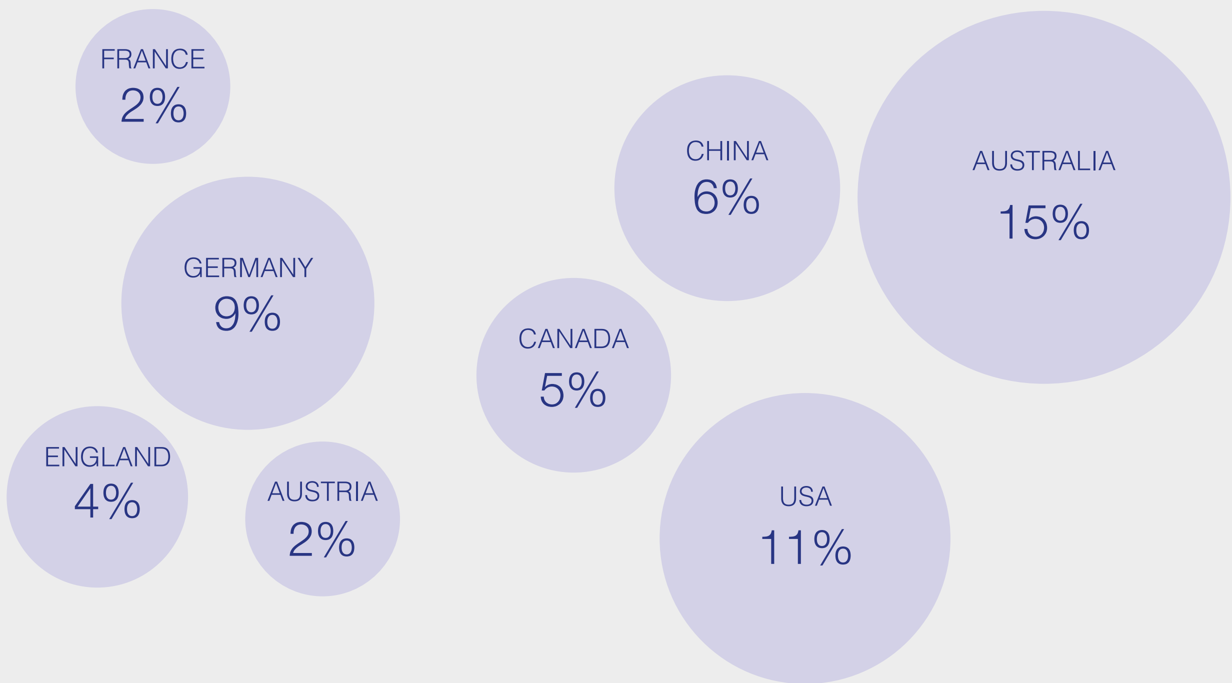
- 26 NEW RHD ENROLMENTS
- 16 POSTGRAD COMPLETIONS
- 10 VISITING STUDENTS
- 8 OCCUPATIONAL TRAINEES

END USER LINKS

- 19 BRIEFINGS
- 6261 UNIQUE WEBSITE HITS
- 10 MEDIA RELEASES
- 11 EDITORIAL BOARDS

COLLABORATIVE PUBLICATIONS

In 2015, the Centre's publications were a result of the Centre's successful collaborations. Many EQuS research findings have been published in a wide range of international scientific journals, books and conference papers. Our most fruitful international collaborations were with the USA, Germany, China and Canada.



Percent of total EQuS publications per collaborating country

NORTH AMERICA & CANADA
16 PUBLICATIONS

EUROPE & RUSSIA
24 PUBLICATIONS

ASIA PACIFIC*
9 PUBLICATIONS

* Excluding Australia

PUBLICATIONS HIGHLIGHTS

HYPER-POLARIZED NANODIAMOND FOR NMR

E. Rej, T. Gaebel, T. Boele, D. E. J. Waddington and D. J. Reilly

READ PAPER

The use of hyperpolarized agents in magnetic resonance, such as 13C-labelled compounds, enables powerful new imaging and detection modalities that stem from a 10,000-fold boost in signal. A major challenge for the future of the hyperpolarization technique is the inherently short spin-relaxation times, typically <60 s for 13C liquid-state compounds, which limit the time that the signal remains boosted. Here we demonstrate that 1.1% natural abundance 13C spins in synthetic nanodiamond can be hyperpolawrized at cryogenic and room temperature without the use of free radicals, and, owing to their solid-state environment, exhibit relaxation times exceeding 1 h. Combined with the already established applications of nanodiamonds in the life sciences as inexpensive fluorescent markers and non-cytotoxic substrates for gene and drug delivery, these results extend the theranostic capabilities of nanoscale diamonds into the domain of hyperpolarized magnetic resonance.

MEASUREMENTS ON THE REALITY OF THE WAVEFUNCTION

M. Ringbauer, B. Duffus, C. Branciard, E. G. Cavalcanti, A. G. White and A. Fedrizzi

READ PAPER

Quantum mechanics is an outstandingly successful description of nature, underpinning fields from biology through chemistry to physics. At its heart is the quantum wavefunction, the central tool for describing quantum systems. Yet it is still unclear what the wavefunction actually is: does it merely represent our limited knowledge of a system, or is it an element of reality? Recent no-go theorems argued that if there was any underlying reality to start with, the wavefunction must be real. However, that conclusion relied on debatable assumptions, without which a partial knowledge interpretation can be maintained to some extent. A different approach is to impose bounds on the degree to which knowledge interpretations can explain quantum phenomena, such as why we cannot perfectly distinguish non-orthogonal quantum states. Here we experimentally test this approach with single photons. We find that no knowledge interpretation can fully explain the indistinguishability of non-orthogonal quantum states in three and four dimensions. Assuming that some underlying reality exists, our results strengthen the view that the entire wavefunction should be real. The only alternative is to adopt more unorthodox concepts such as backwards-in-time causation, or to completely abandon any notion of objective reality.

EQuS researchers publish in the world's best journals in the field of Quantum Physics

EXPLORING THE QUANTUM CRITICAL BEHAVIOUR IN A DRIVEN TAVIS–CUMMINGS CIRCUIT

M. Feng, Y.P. Zhong, T. Liu, L.L. Yan, W.L. Yang, J. Twamley and H. Wang

READ PAPER

Quantum phase transitions play an important role in many-body systems and have been a research focus in conventional condensed-matter physics over the past few decades. Artificial atoms, such as superconducting qubits that can be individually manipulated, provide a new paradigm of realising and exploring quantum phase transitions by engineering an on-chip quantum simulator. Here we demonstrate experimentally the quantum critical behaviour in a highly controllable superconducting circuit, consisting of four qubits coupled to a common resonator mode. By off-resonantly driving the system to renormalize the critical spin-field coupling strength, we have observed a four-qubit nonequilibrium quantum phase transition in a dynamical manner; that is, we sweep the critical coupling strength over time and monitor the four-qubit scaled moments for a signature of a structural change of the system's eigenstates. Our observation of the nonequilibrium quantum phase transition, which is in good agreement with the driven Tavis–Cummings theory under decoherence, offers new experimental approaches towards exploring quantum phase transition-related science, such as scaling behaviours, parity breaking and long-range quantum correlations.

ENHANCED OPTICAL TRAPPING VIA STRUCTURED SCATTERING

M. A. Taylor, M. Waleed, A. B. Stilgoe, H. Rubinsztein-Dunlop and W. P. Bowen

READ PAPER

Interferometry can completely redirect light, providing the potential for strong and controllable optical forces. However, small particles do not naturally act like interferometric beamsplitters and the optical scattering from them is not generally thought to allow efficient interference. Instead, optical trapping is typically achieved via deflection of the incident field. Here, we show that a suitably structured incident field can achieve beamsplitter-like interactions with scattering particles. The resulting trap offers order-of-magnitude higher stiffness than the usual Gaussian trap in one axis, even when constrained to phase-only structuring. We demonstrate trapping of 3.5–10.0 μm silica spheres, achieving a stiffness up to 27.5 ± 4.1 times higher than was possible using Gaussian traps as well as a two-orders-of-magnitude higher measured signal-to-noise ratio. These results are highly relevant to many applications, including cellular manipulation, fluid dynamics, micro-robotics and tests of fundamental physics.

KEY PERFORMANCE AREAS

Research findings

Performance measure	Target	Outcome
Number of research outputs - Papers in international peer review journal	85	97
Quality of research outputs 90% papers in high impact journals	77	88
Number of invited talks/papers/keynote lectures given at major international meetings	20-30	78
Media releases	10	10
Number and nature of commentaries about the Centre's achievements (electronic media, newspapers and magazine articles)	10	41

Research training and professional education

Performance measure	Target	Outcome
Number of attended professional training courses for staff and postgraduate students	10	32
Number of Centre attendees at all professional training courses	35	234
Number of new postgraduate students working on core Centre research supervised by Centre staff (including PhD, Masters by research and Masters by coursework)	17	26
Number of new postdoctoral researchers recruited to the Centre working on core Centre research	9	12
Number of new Honours students working on core Centre research and supervised by Centre staff	10-15	12
Number of postgraduate completions and completion times, by students working on core Centre research and supervised by Centre staff	14 PhD 3 Masters	9 PhD 7 Masters by Research

Research training and professional education, cont

Performance measure	Target	Outcome
Number of Early Career Researchers (within five years of completing PhD) working on core Centre research	19	26
Number of students mentored	71	124
Number of mentoring programs	2	5

International, national and regional links

Performance measure	Target	Outcome
Number of international visitors and visiting fellows	34	81
Number of national and international workshops held/ organised by the Centre	2	10
Number of visits to laboratories and facilities (overseas research collaborative visits)	80	119
Examples of relevant interdisciplinary research supported by the Centre	Quantum effects in biology; Biosensors; and Microwaves electronics and Electrical engineering	Details of relevant interdisciplinary research supported by the Centre can be found on the Research Project Reports on pages 28 to 47

End-user links

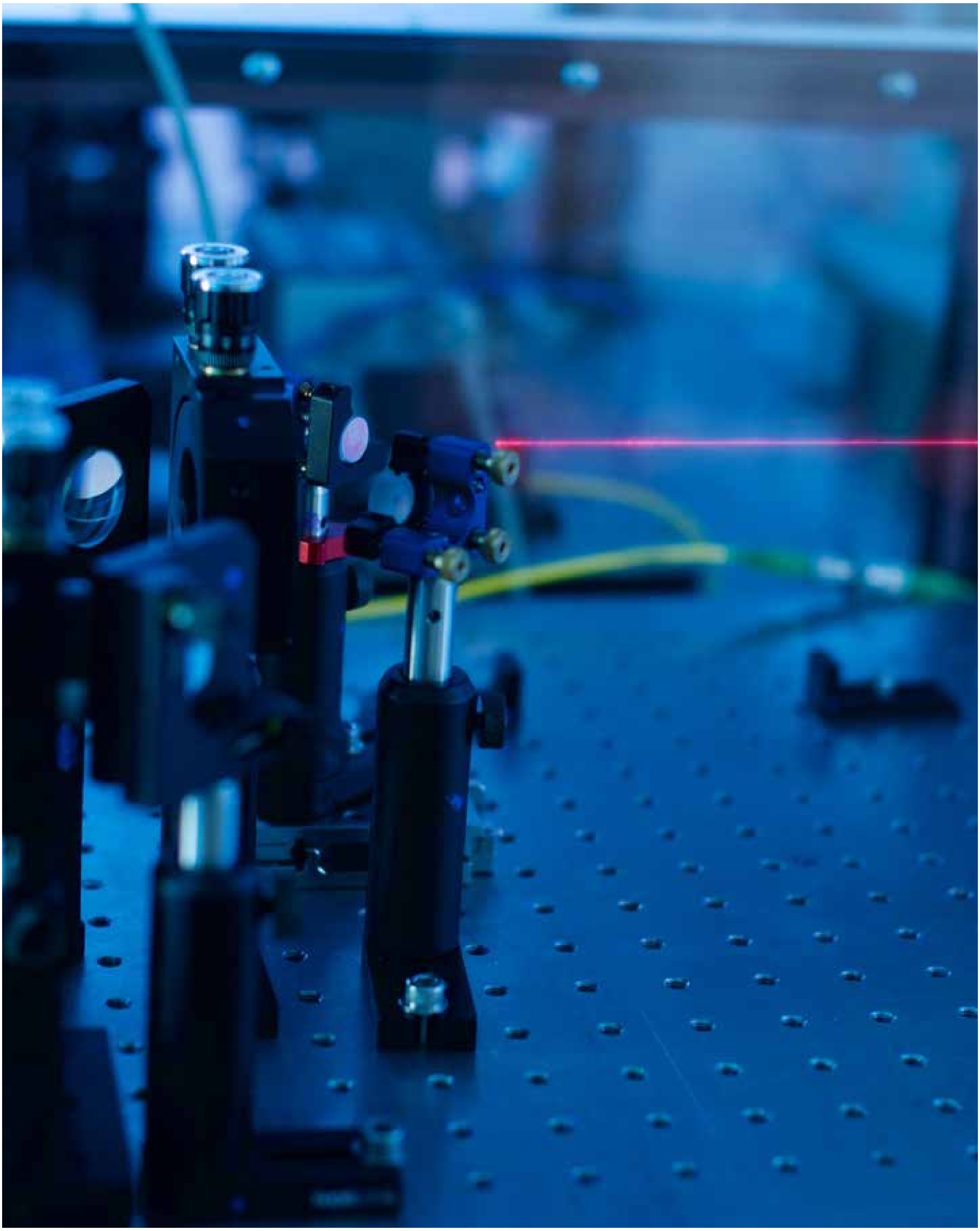
Performance measure	Target	Outcome
Number of government, industry and business community briefings	10	19
Number and nature of public awareness programs	12 School visits 3 Science teacher workshops	20 School visits 3 Science teacher workshops
Currency of information on the Centre's website Number of revisions	6	12
Number of website hits (unique)	1200	6261 unique users

End-user links, cont.

Performance measure	Target	Outcome
Number of public talks given by Centre staff	10	34

Organisational support

Performance measure	Target	Outcome
Annual Cash contributions from Collaborating Organisations	University of Queensland $600,000; Macquarie University $250,000; University of Sydney $200,000; University of Western Australia $87,500; University of New South Wales $50,000	University of Queensland $600,000; Macquarie University $249,462 (note: shortfall of $538 against target is income additionally contributed in 2011); University of Sydney $200,000; University of Western Australia $93,625; University of New South Wales $50,000
Annual In-Kind contributions from Collaborating Organisations	University of Queensland $1,764,934; Macquarie University $322,697; University of Sydney $5,089,813; University of Western Australia $1,213,751; University of New South Wales $137,635	University of Queensland $2,353,158; Macquarie University $1,138,766; University of Sydney $5,089,813; University of Western Australia $5,081,586; University of New South Wales $2,058,605
Annual Cash contributions from Partner Organisations	University of Innsbruck $5,000; University of Ulm $4,506; Imperial College $5,057	University of Innsbruck $5,000; University of Ulm $4,506; Imperial College $5,057
Annual In-Kind contributions from Partner Organisations	University of Vienna $10,000; Imperial College $9,119; University of Ulm $12,392; University of Innsbruck $21,609; Perimeter Institute for Theoretical Physics $30,000; University of Copenhagen $65,000	University of Vienna $10,000; Imperial College $9,119; University of Ulm $22,500; University of Innsbruck $21,609; Perimeter Institute for Theoretical Physics $30,000; University of Copenhagen $65,000
Other research income secured by Centre staff (list research from ARC grants, other Australian competitive grants, grants from the public sector industry and CRCs and other research income separately)	$500,000	$13,599,177 (details over page under 'Income derived from other sources')
Number of new organisations collaborating with, or involved in, the Centre	2	5



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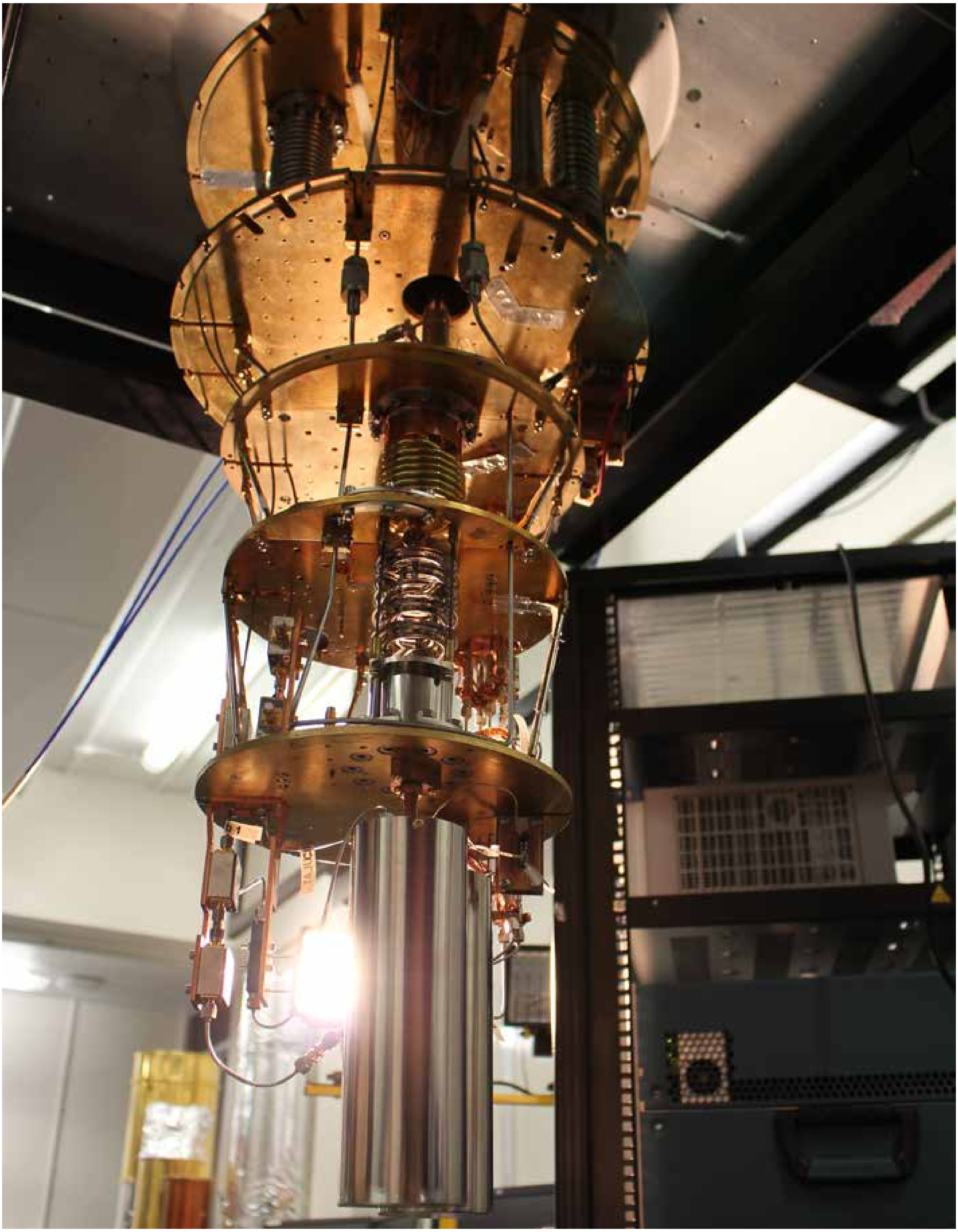

FINANCIAL REPORT

2015 Statement of Income and Expenditure

INCOME	2014 ACTUALS	2015 ACTUALS	2016[1] FORECASTS
ARC Centre of Excellence Grant			
Base Income	3,500,000	3,500,000	3,500,000
Indexation on Base Income	449,815	520,557	588,905
Administering and Collaborating Organisation Contributions			
The University of Queensland	600,000	600,000	600,000
Macquarie University[2]	250,000	249,462	250,000
The University of Sydney	200,000	200,000	200,000
The University of Western Australia			
UWA cash contribution as per agreement	87,500	87,500	87,500
UWA additional cash contribution	6,125	6,125	6,125
The University of New South Wales	50,000	50,000	50,000
Partner Organisation Contributions			
The University of Innsbruck	5,000	5,000	5,000
University of Ulm	4,506	4,506	4,506
Imperial College	5,057	5,057	5,057
Overseas Government Organisations and Other Grants			
New South Wales State Leveraging Fund (SLF)[3]	250,000	-250,000	
Intelligence Advanced Research Projects Activity (IARPA)[4]	294,915	349,151	-234,822
UWA other grants[5]	-45,600		
TOTAL INCOME	**5,657,318**	**5,372,358**	**5,062,271**

EXPENDITURE	2014 ACTUALS	2015 ACTUALS	2016(1) FORECASTS
Salaries	3,231,809	2,596,793	3,116,151
Scholarships	301,424	295,462	354,555
Equipment and Maintenance	1,061,134	1,088,714	1,306,457
Travel	670,884	583,473	700,167
Other Expenditure	372,727	309,061	370,874
Intelligence Advanced Research Projects Activity (IARPA)	123,977	264,424	
Partner Organisations	14,563	14,563	14,563
TOTAL EXPENDITURE	**5,776,518**	**5,152,490**	**5,862,766**
ANNUAL SURPLUS/(DEFICIT)	**-119,200**	**174,868**	**-800,495**
BALANCE BROUGHT FORWARD FROM PREVIOUS YEAR	**1,213,204**	**1,094,004**	**1,268,872**
TOTAL CARRYFORWARD TO NEXT YEAR	**1,094,004**	**1,268,872**	**468,376**

Notes:
(1) 2016 forecasts are projected expenditure and actuals in 2016 is subject to change.
(2) Macquarie University 2015 co-contribution of $249,462 is $538 short of its $250,000 co-contribution due to an additional amount of the same value already contributed in 2011.
(3) In 2015, income of $250,000 has been reversed out to exclude New South Wales State Leveraging Fund (SLF) recorded in 2014. The SLF income is not part of the Centre Agreement. No expenses in previous years have been recorded, therefore no reversal of expenditure is required.
(4) In 2016, the remaining income for Intelligence Advanced Research Projects Activity (IARPA) is expected to be reversed and will be reflected as a reversal in income. This IARPA project is not part of the Centre Agreement.
(5) In 2014, income of $45,600 has been reversed out to exclude internal grants from the University of Western Australia (UWA) recorded in 2013. These grants are not part of the EQuS Centre Agreement. No expenses in previous years have been recorded, therefore no reversal of expenditure is required.

INCOME DERIVED FROM OTHER SOURCES

The Centre is successful in leveraging off its Centre of Excellence grant and has attracted other research grants and consultancies in 2015. These additional grants and consultancies are not part of the Centre Agreement, but are listed here to provide grants and consultancies associated with the Centre for 2015 only.

Funding body/scheme	Details*	2015 Funding (AUD)
OVERSEAS UNIVERSITY/RESEARCH INSTITUTE		
Asian Office of Aerospace Research and Development	White, A., Pereira De Almeida, M., Fedrizzi, A.; Computational complexity of bosons in linear networks.	75,669
German Academic Exchange Service (DAAD)	Fedorov. A.; Group of Eight - Australia (2013001743); Microwave photon engineering with superconducting qubit chains.	9,800
Templeton World Charity Foundation	White, A. & Milburn, G.; International Funding - Bahamas (TWCF0064/ AB38); The causal power of information in a quantum world.	693,472
OVERSEAS GOVERNMENT ORGANISATION		
Airforce Office of Scientific Research (AFOSR) / Asian Office of Aerospace Research and Development (AOARD)	Bowen, W.; Quantum microrheology.	399,992
Intelligence Advanced Research Projects Activity (IARPA)	Reilly, D., Bartlett, S.D., Doherty, A,; Multi-qubit systems bases on electron spins in coupled quantum (included in the EQuS Financial Statement)	349,151
Intelligence Advanced Research Projects Activity (IARPA)	Biercuk, M.J., Flammia, S.T.; Modular universal scalable ion-trap quantum computer (not included in the EQuS Financial Statement)	414,336
US Army Research Office	Flammia, S.T.; Robust and device-independent benchmarking for fault-tolerant quantum computation.	414,286
US Army Research Office	Flammia,S.T.; Certified topological quantum computation.	278,647
US Army Research Office	Reilly, D.; Enhanced readout performance for quantum dot spin qubit.	1,052,122
US Army Research Office	Biercuk, M.J.; Quantum control engineering.	1,168,122
US Army Research Office	Bartlett, S.D.; Photonic quantum characterization, verification, and validation.	1,193,406
INDUSTRY/PRIVATE		
Chinese Oscillator	Tobar, M; Chinese Oscillator	190,000
Microsoft Corporation	Reilly, D.; Microsoft Corporation, Microsoft Station Q.	3,780,062

Funding body/scheme	Details*	2015 Funding (AUD)
ADMINISTERING AND COLLABORATING ORGANISATIONS		
The University of New South Wales	Duty. T.; The University of New South Wales, Silver Star Awards.	35,000
The University of Queensland	White, A.; UQ co-contribution to ARC Centre of Excellence for Quantum Computation and Communication.	50,700
The University of Queensland	Bowen, W., Fedorov, A., McCulloch, I., Milburn, G., Stace, T., White, A.; The University of Queensland, Advanced Superfluid Physics Facility.	161,229
The University of Queensland	Milburn, G.; UQ Internal Grant, UQ Vice-Chancellor's Research and Teaching Fellowship.	23,580
The University of Queensland	White, A.; UQ Vice-Chancellor's Research and Teaching Fellowship; Disruptive information technology: Putting the photon into photonics.	169,347
The University of Queensland	Li, B.; UQ Postdoctoral Research Fellowship; Microfluidic magnetic resonance imaging with optomechanical magnetometers.	104,766
The University of Sydney	Biercuk, M.J.; The University of Sydney, International Program Development Fund.	15,000
The University of Sydney	Biercuk, M.J.; DVCR AISNT Accelerator	41,000
The University of Sydney	Biercuk, M.J.; DVCR AISNT Accelerator	136,000
The University of Sydney	Bartlett, S. DVCR AINST Accelerator	75,000
The University of Sydney	Biercuk, M.J.; DVCI International Research Collaborative Award	14,500
The University of Western Australia	Creedon, D.; The University of Western Australia research funding; Coupling crystal resonators and novel cavities to highly coherent quantum devices.	8,800
The University of Western Australia	Tobar, M.; The University of Western Australia research funding; Linking optical and microwave frequencies with application to precision and quantum limited information transfer and fundamental tests.	15,000
OTHER ARC GRANTS		
ARC Future Fellowship	Molina-Terriza, G.; Understanding nature with twisted photons. (FT110100924).	89,707
ARC Future Fellowship	Flammia, S.T.; Powerful techniques and methods of machine learning to identify, characterise, and correct noise sources in the next generation of quantum information processors (FT130101744).	153,669
ARC Future Fellowship	Bowen, W.; Optomechanical metrology: pushing optical sensing to its limit (FT140100650).	223,103

Funding body/scheme	Details*	2015 Funding (AUD)
ARC Future Fellowship	Fedorov, A.; Distributed quantum networks with cascaded superconducting circuits (FT140100338).	192,511
ARC Future Fellowship	McCulloch, I.; Simulating quantum states of matter: connecting theory to applications in science and technology (FT140100625).	191,137
ARC Future Fellowship	Stace, T.; Quantum-Assisted Sensing (FT140100952).	181,026
ARC Linkage	Biercuk, M.J.; Foundation technology for quantum measurement, sensing and computing (LP130100857).	125,000
ARC Linkage	Bowen, W.; Optomechanical refrigeration of electronic circuits (LP140100595).	100,000
ARC Linkage	Biercuk, M.J.; Optical technology for quantum science (LP150101188).	55,000
ARC Linkage	Reilly, D.; Inductively-coupled plasma etching facility (LE150100172).	270,000
ARC Discovery	Bartlett, S. & Doherty, A.; Bulk-boundary correspondence in quantum many-body systems (DP130103715).	90,000
ARC Discovery	Biercuk, M.J.; Frequency standards with breakthrough performance: engineering immunity to local oscillator instabilities using dynamical error suppression (DP130103823).	75,000
ARC Discovery	Tobar, M.; Precision measurement to test fundamental physics (DP130100205).	120,000
ARC Discovery	Rubinsztein-Dunlop, H.; Force microscopy with arbitrary optically-trapped probes and application to internal mechanics of cells (DP140100753).	150,000
ARC Discovery	Bowen, W.; Ultraprecise sensing with microcavity optomechanics (DP140100734).	201,500
ARC Discovery	Fedorov, A.; Quantum networks based on superconducting circuits and dissipative channels (DP150101033).	150,000
ARC Discovery	Milburn, G.; Grossing quantum-classical boundaries in a single particle (DP150101863).	140,000
ARC Centres of Excellence	White, A.; ARC Centre of Excellence for Quantum Computation and Communication Technology (CE1101027).	222,538
TOTAL		13,599,177

*** Only named EQuS researchers are listed.**

COVER IMAGE
Quantum photonics for investigating the light-matter interface, UQ Node. *(photo credit Christina Giarmatzi)*

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