AUSTRALIAN RESEARCH COUNCIL
Linkage Projects
Proposal for Funding Commencing in 2018

LP

PROJECT ID: LP180100096

First Investigator: Dr Erik Streed

Admin Org: Griffith University

Total number of sheets contained in this Proposal: 137

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Part A - Administrative Summary (LP180100096)

A1. Proposal Working Title

(Provide a short working title of no more than 75 characters (approximately ten words).)

A Memory Powered Engine

A2. Person Participant Summary

(Add all people participating in this Proposal as a Chief Investigator or Partner Investigator. A Chief Investigator must: not be undertaking a Higher Degree by Research during the Project; reside predominantly in Australia for the Project Activity Period; and be an employee for at least 0.2 FTE at an Eligible Organisation, or be a holder of an Emeritus Appointment (see A3 and A6 of the Funding Rules) at an Eligible Organisation. Note that a person's RMS email address must be used to invite them to participate in this Proposal. Refer to the Instructions to Applicants for further information.)

Number	Name	Participant Type	Current Organisation(s)	Relevant Organisation
1	Dr Erik Streed	Chief Investigator	Griffith University	Griffith University
2	Dr Andre Carvalho	Chief Investigator	Griffith University	Griffith University
3	Prof Joan Vaccaro	Chief Investigator	Griffith University	Griffith University
4	Prof Stephen Barnett	Partner Investigator	University of Glasgow, UK	University of Glasgow, UK
5	Dr Luke Uribarri	Partner Investigator	Lockheed Martin (US)	Lockheed Martin Corporation

A3. Organisation Participant Summary

(Add all organisations participating in this Proposal. Refer to the Instructions to Applicants for further information.)

Number	Name	Participant Type
1	Griffith University	Administering Organisation
2	Lockheed Martin Corporation	Partner Organisation
3	University of Glasgow, UK	Other Organisation

A4. Proposal Summary

(Provide a Proposal summary of no more than 750 characters (approximately 100 words) focusing on the aims, significance and expected outcomes of this Project. Write your Proposal Summary simply, clearly and in plain English. If your Proposal is successful, the Proposal Summary is used to give the general community an understanding of your research. Avoid the use of acronyms, quotation marks and upper case characters. Refer to the Instructions to Applicants for further information.)

Classical heat engines, such as petrol motors, convert thermal energy from hot gases into useful work, but with limited efficiency as much of the thermal energy is lost as waste heat. The project aims to combine experimental techniques in quantum information processing with recent theoretical developments in quantum thermodynamics to demonstrate a proof-of-concept heat engine that converts thermal energy into work with 100% efficiency. A heat engine of this kind would provide significant benefits to Australia with its potential to revolutionise how we store and use energy. The project will enable Griffith University to continue its pioneering role in developing this technology and to maintain long-term international collaborations.

A5. Benefit and Impact Statement

(In no more than 750 characters (approximately 100 words), outline the intended benefit and impact of the Project. Write your Benefit and Impact Statement simply, clearly and in plain English. Refer to the Instructions to Applicants for further information.)

Extracting work from heat is the underlying thermodynamic process in transportation and electricity generation.

This project leverages quantum physics to seek solutions that require fewer precious resources, better leverage abundant resources, and results in less energy waste. The first generation of application of quantum physics to electrical and optical devices resulted in the development of the transistor and the laser. The second generation is leading to the development of quantum computation, communications, and encryption. Our project aims for a similar transformative advance by laying the applied foundations for a new class of technology based on quantum thermodynamics- quantum enhanced heat engines.

A6. Is this Proposal similar to a previously submitted unsuccessful Proposal in the LP18 round?

(The ARC would consider a Proposal to be similar if the aims and methodology of the Project Description and Participants have not substantially changed.)

No

A7. Please provide the Proposal ID and detail how this Proposal differs from the previous Proposal(s).

(For each of the unsuccessful proposals submitted in the LP18 round, please enter the Proposal ID and describe in no more than 750 characters (approximately 100 words), how the current Proposal differs from the previously submitted proposal(s).)

Part B - Classifications and Other Statistical Information (LP180100096)

B1. Does this Proposal fall within one of the Science and Research Priorities?

Yes

Science and Research Priority	Practical Research Challenge
Energy	New clean energy sources and storage technologies that are efficient, cost-effective and reliable.

B2. Field of Research (FoR)

(Select up to three classification codes that relate to your Proposal. Note that the percentages must total 100%.)

Code	Percentage
020603 - Quantum Information, Computation and Communication	60
020304 - Thermodynamics and Statistical Physics	40

B3. Socio-Economic Objective (SEO-08)

(Select up to three classification codes that relate to your Proposal. Note that the percentages must total 100%.)

Code	Percentage
970102 - Expanding Knowledge in the Physical Sciences	60
850702 - Energy Conservation and Efficiency in Transport	20
850602 - Energy Storage (excl. Hydrogen)	20

B4. Interdisciplinary Research

(This is a 'Yes' or 'No' question. If you select 'Yes' two additional questions will be enabled:
1. Specify the ways in which the research is interdisciplinary by selecting one or more of the options below.
2. In no more than 375 characters (approximately 50 words), indicate the nature of the interdisciplinary research involved.)

Does this Proposal involve interdisciplinary research?

No

Specify the ways in which the research is interdisciplinary by selecting one or more of the options below.

In no more than 375 characters (approximately 50 words), indicate the nature of the interdisciplinary research involved.

B5. Does the proposed research involve international collaboration?

(This is a 'Yes' or 'No' question. If you select 'Yes' two additional questions will be enabled:
1. Specify the nature of the proposed international collaboration by selecting one or more of the options below.
2. Specify the countries which are involved in the international collaboration.)

Yes

B6. What is the nature of the proposed international collaboration activities?

(Select all options from the drop-down list which apply to this Proposal by clicking on the 'Add' button each time you select an option.)

Face to face meetings
Attendance at and/or hosting of workshop or conference
Correspondence: eg email; telephone; or video-conference

B7. If the proposed research involves international collaboration, specify the country/ies involved

(Commence typing in the search box and select from the drop-down list the name of the country/ies of collaborators who will be involved in the proposed Project. Note that Australia is not to be listed and is not available to be selected from the drop-down list.)

United States of America
Scotland

B8. How many PhD, Masters and Honours places will be filled as a result of this Project?

(The ARC is capturing the number of Research Students that would be involved in this Proposal if it is funded. Enter the number of student places (full-time equivalent) that will be filled as a result of this Project.)

Number of Research Student Places (FTE) - PhD

2

Number of Research Student Places (FTE) - Masters

0

Number of Research Student Places (FTE) - Honours

2

Part C - Project Description (LP180100096)

C1. Project Description

(Upload a Project Description as detailed in the Instructions to Applicants in no more than ten A4 pages and in the required format.)

Uploaded PDF file follows on next page.

PROJECT TITLE: **AN ENGINE POWERED BY MEMORY**

AIMS AND BACKGROUND

Background

Imagine powering your mobile phone using just water! Water has enough thermal energy for the task: on a mass-for-mass comparison, water at room temperature has about as much thermal energy as the stored electrical energy in a lithium ion battery. The catch, however, is that with available technology, the water's thermal energy is able to be extracted in a useful form only if a minimum amount of waste heat flows to a colder environment. Fig. 1(a) illustrates the general principle for a classical heat engine. An amount Q_h of heat is extracted from a hot thermal reservoir (e.g. the water) and converted into a lesser amount of useful energy as the work $W = Q_h - Q_c$, where Q_c is waste heat that flows to a colder reservoir. This possibility is not restricted to just water—there's a lot of untapped thermal energy in objects all around us, if only we could harness it.

Now imagine that a new device could be constructed that is capable of converting *all* of the thermal energy of the water into useful work without a colder environment and the loss of waste heat. Although this may appear to be unphysical, in fact the Laws of Thermodynamics do not forbid devices of this kind.

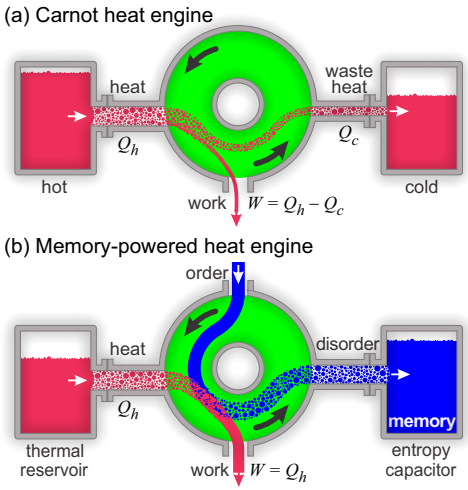

Fig. 1: Schematics of heat and entropy flow in a (a) Carnot engine and (b) memory-powered heat engine.

Indeed, our energy-extraction device is really an example of Maxwell's demon [1] who takes heat from a single thermal reservoir and converts it into useful work. For example, the demon could take a gas, which is initially in thermal contact with the water, and separate fast moving molecules from slow ones to create two gases, one hot and the other cold. An ordinary heat engine could then produce work W from the two gases. Remixing the gas and bringing it back into contact with the water would draw more thermal energy from it, and so on. The caveat, as shown by Landauer and Bennett [2, 3], is that the disordered information that the demon accumulates in the process of sorting the molecules needs to be erased, and that erasure comes at a cost at least as great as the work W extracted. As such, there is no net advantage. But, in a **breakthrough** paper, CI Vaccaro and PI Barnett recently showed that the erasure cost need not be in terms of energy — it could, instead, be paid in terms of another conserved quantity, such as angular momentum [4–7]. As illustrated in Fig. 1(b), this allows an amount Q_h of heat to be converted *entirely* into work, i.e. $W = Q_h$. The entropy from the heat is "dumped" into a bit of the additional conserved quantity, which changes from being ordered to disordered. This entropy is, essentially, a *memory* of the disordered nature of the heat Q_h, and the additional conserved quantity acts as an *entropy capacitor* for storing it. Rather like a rechargeable battery, once the capacitor reaches maximum entropy, it needs to be removed, have its memory erased, and be returned, so that the engine can keep running. In effect, ***our heat engine is powered by erased memory*** that enables it to produce work even from ambient heat.

As a memory-powered engine requires the storage and transport of memory rather than energy, it has potential to dramatically change the nature of energy harnessing, storage and transport. Even a modest improvement in these aspects of energy technology could have significant economic and environmental repercussions.

Aims and objectives

The overarching **aim** of this project is to model, study, and demonstrate memory-powered heat engines (MPEs)[1] using ion trap technology as a proof-of-concept. Trapped atomic ions are an established experimental system for investigating quantum physics with well-developed techniques for precision manipulation of external motional and internal memory type states. The proposal is principally an experimental follow-up to an earlier theory-focused ARC Linkage Project LP140100797, led by CI Vaccaro and also partnered with Lockheed Martin Corporation (LMC)[2], that developed a number of heat engine designs including one based on an ion trap (e.g. [8, 9]). The proposal also incorporates a theoretical component to provide not only modelling and design support for the experimental demonstration using trapped ions, but also to investigate the scalability issues associated with long-term future development in other systems. In short, the broad objectives of the proposal are to:

Objective 1. Demonstrate the operation of a memory-powered engine experimentally, and

Objective 2. Investigate memory-powered engines theoretically.

[1] Throughout the text a "memory-powered heat engine" will be simply referred to as a "MPE", for brevity.

[2] From now on, the Partner Organisation will be referred as LMC, for brevity.

Prior work in the research field

The project lies in the emerging research field of Quantum Thermodynamics, an area that has seen impressive progress in recent years thanks to its increasingly-explored relation with quantum information theory [10, 11]. Landauer's erasure principle and its connections to quantum heat engines have been of particular interest [12, 13]. There are now a number of quantum heat engine designs to complement Scovil and Schulz-DuBois' maser model [14] as well as methods for experimentally determining the properties of the engines [15–17] and experimental demonstrations [18,19]. All these contributions, however, involve only energy exchanges and heat engines that operate between hot and cold thermal reservoirs as illustrated in Fig. 1(a). In marked contrast to this energy-centred perspective, CI Vaccaro and PI Barnett [5, 6, 20] applied Jaynes' generalised statistical mechanics [21] to information erasure to derive the breakthrough result mentioned above, and discover that new types of heat engines were possible [5]. The performance of generalised heat engines has now been studied [22] under an information-theoretic framework of thermodynamics with multiple conserved quantities [23]. In terms of implementations, CIs Carvalho and Vaccaro *et al.* [8] have designed and analysed a quantum-dot version of a MPE. Baumgratz *et al* [24] are attempting a heat engine design based on a similar principle using the spin Hall effect. CIs Carvalho, Vaccaro and Streed [9] have recently designed and analysed a MPE based on trapped ions—it's experimental feasibility led to this LP18 proposal, which aims to give the first experimental demonstration that MPEs are, indeed, possible.

Outline of our approach[3]

The experimental demonstration for our **Objective 1** will use well-developed techniques for quantum information processing (QIP) with trapped ions. Similar to QIP, we will use the internal hyperfine states of trapped ions as a quantum memory and use lasers to coherently and selectively couple memory states with the motional states. The project will reversibly read the thermal state of an ion crystal's vibrational motion using the spin states of one particular trapped ion. In the process, vibrational energy will be extracted by the control lasers and 1 bit of entropy will be left in the ion's spin states, demonstrating a **single step energy extraction (Task 1.1)**. This is the fundamental functional unit in implementing the MPE. We'll then proceed to investigate scaling up this process through performing **multiple cycles of entropy extraction** either using multiple ions, **one cycle per ion (Task 1.2)** in a Coulomb crystal to store each bit of entropy, or through **entropy concentration in an single ion (Task 1.4)** through using more of the available states. We'll also investigate a proposed **expansion step (Task 1.3)** [9] to increase the efficiency of our entropy extraction cycles through coherently manipulating the thermal state into a temporary higher energy athermal configuration. Finally, we'll complete our proof-of-concept demonstration by showing **energy extraction (Task 1.5)** using an optical cavity to directly measure the work by detecting the photons resulting from a successful engine cycle.

The theoretical component of the project, **Objective 2**, comprises three main tasks. The first is to support the experimental component by **modelling the experimental demonstration in terms of appropriate theory (Task 2.1)** and involves refining the ion trap MPE designed in Linkage Project LP140100797 to match actual experimental parameters and imperfections, as well as analysing experimental data and modelling the expected performance of the engine. This will involve theory CIs Carvalho and Vaccaro working closely with experimental CI Streed when experimental data is available and theoretical modelling is needed. The flow of expertise and information will be bi-directional between the two groups, as needed.

Even though our experimental demonstration will provide the first proof that memory-powered engines work in practice, it is far from what is needed in commercial applications. For this, one would be ideally looking at a system that is practical, scalable, fast, and robust. From the point of view of our industrial partner, investigating these issues is of crucial importance for guiding long-term investment. Accordingly, we plan to **explore alternate MPE designs (Task 2.2)**, where, instead of extracting energy through the laser beams, we will investigate the conversion of thermal energy directly into mechanical work [18], or even electricity. This represents a move towards more practical implementations of MPE, consistent with LMC's long term vision. We also plan to **establish principles for scalable designs (Task 2.3)**. This involves both the investigation of fundamental bounds on entropy storage, as well as the design of protocols to create entropy capacitors with high storage density.

INVESTIGATORS

CI Streed 0.5 FTE (GU) is the Project Leader responsible for managing the project budget, detailed planning and results communication at Griffith University. He is also Experimental Group Leader, using his experience in building and operating pioneering atomic physics apparatus responsible to guide the day-to-day management of the ion trapping experiment, directing the design of experiments,interpretation of data, and implementation of new protocols. Streed has an established track record of engaging with end-users in terms of partnering with LMC in this and a previous Linkage Project LP140100797, as well as with his collaboration with the US Army Research

[3]Full details of the tasks labelled as **(Task n.n)** can be found in the section APPROACH AND TRAINING.

Laboratory in developing and fabricating aberration corrected external vacuum Fresnel lenses. Streed is also in discussions with LMC and their strategic partner Element 6 in assessing the feasibility of MPE demonstrations using nitrogen-vacancy colour centres in diamond. Streed will mentor the Experimental RF and the associated experimental RHD students. He has previously supervised 7 Honours students, formally advised 2 PhD graduates, and informally supervised another PhD graduate as a post-doc. He is presently supervising 1 Honours student and 4 PhD students, one of whom is finalising his thesis for submission. Streed has a continuing balanced profile position and will commit 0.5 FTE to this project comprising 0.28 FTE through a Teaching Relief ($100k) and 0.22 FTE from his standard 0.4 FTE research profile.

CI Carvalho 0.4 FTE (GU) is the Theoretical Group Leader. He will have primary responsibility for the research direction and planning of the theoretical aspects of the project. He will manage the daily activities of the theory group, mentor the theory RF and RHD students, organise weekly group meetings, and coordinate the interaction and communication with the experimental part of the project. He has expertise in quantum optics and quantum information, with a number of important contributions in the analytical and numerical modelling of ion trap systems and their manipulation with laser fields, which will be invaluable for modelling the dynamics of heat engine proposals. He has an extensive experience in establishing successful collaborations, including with CI Streed [25] and CI Vaccaro [8]. Since 2017, when he moved to Griffith University, he has been an active member of the collaboration with LMC, participating in meetings and reporting to the partners, demonstrating his potential in engaging with end-users. He has supervised 8 Honours students and co-supervised 1 Masters and 5 PhD students to completion, and is currently supervising one co-supervising two PhD students. His research-only contract allows him to 0.4 FTE to this project. His role as Theoretical Group Leader will mentored by CI Vaccaro.

CI Vaccaro 0.3 FTE (GU) has wide expertise in fundamental aspects of quantum physics, including quantum information theory, and will play a leading role in conceptual issues of the project. She will mentor CI Streed and CI Carvalho and assist the mentoring of the theory RF and RHD students at Griffith University. Her capacity to undertake this work is demonstrated by her and PI Barnett being the originators of the erasure concept [4–7] that underpins this proposal. She led the design of a heat engine using the new erasure technique in quantum dot technology [8]. She will commit 0.3 FTE to the project with the aid of a teaching relief requested in this proposal. She has engaged with end-users in partnering with LMC in this and Linkage Project LP140100797. She was a panellist representing Academia-Industry engagement at the joint Lockheed Martin and Defence Science Institute event in Sydney in Dec 2016. She has supervised 2 PhD students as co-principle supervisor, 3 as associate supervisor and 4 Honours students and is currently co-principle supervisor to 2 PhD students.

PI Barnett 0.1 FTE (Uni. of Glasgow) is widely acknowledged as a leading theoretical physicist as his election to the Fellowship of the Royal Society in 2006 clearly testifies. He has successfully completed a large number of grants awarded by various funding agencies including the Engineering and Physical Sciences Research Council in the UK. He will provide creative insight and his expertise in theoretical physics in collaboration with CIs Vaccaro & Carvalho in the theoretical component of the project. He will also act as mentor to CI Vaccaro. He and CI Vaccaro are the originators of the erasure concept [4–7] that underpins this proposal, and he was a PI on the ARC Linkage Project LP140100797 with CI Vaccaro in partnership with LMC, which demonstrates his capacity for this project and potential for collaboration with end-users. He is a full-time Research Professor, fully funded by the Royal Society, which enables him to contribute a 0.1 FTE to the project.

PI Uribarri 0.05 FTE (LMC), Deputy to the Chief Scientist, will provide intellectual input through his knowledge of energy storage systems based on quantum thermodynamics and non-linear optical properties of quantum dots as well as provide assistance with technology transfer and application development. He will also coordinate activity between CIs Streed, Carvalho and Vaccaro and LMC.

Chief Scientist Dr Ned Allen 0.05 FTE (LMC) will provide guidance regarding potential new applications and extensions of the core concepts and his **Technical Assistant 0.05 FTE (LMC)** will assist with protection of intellectual property generated by the Project.

Experimental Research Fellow (ERF) RF2.1 1.0 FTE will have responsibility for the in-lab operation of the experiments and assist with the supervision of the RHD and Honours students. The experimental RF will be responsible for leading the experimental data taking to accomplish the objectives in Aim 1 as well as the leader in construction of the purpose built Quantum Thermo ion trap and $D_{5/2}$ Shelving Laser 411 nm system. They will be supported through mentorship by CI Streed and in-lab assistance from the RHD and Honours students.

Theory Research Fellow (TRF) RF1.4 1.0 FTE will work on fine tuning our model for the ion trap MPE, performing analytical and numerical work that include experimental parameters and imperfections (**Task 2.1**). This is a time-intensive task that involves continuous flow of information between theory and experiment, and is of

fundamental importance for the project. The RF will also be involved in the investigation of scalable design for entropy capacitors (**Task 2.3**) and, as part of their training, will assist with the supervision of the RHD student.

Experimental RHD student 1.0 FTE for 2 years will be responsible for the assembly of the Ion Addressing AOMs, the 976 nm repumper/Raman system, as well as assisting the assembly of the 411 nm narrow linewidth laser system. Under the supervision of CI Streed and the Experimental RF, the student will take responsibility on the experimental data taking and data analysis.

Theory RHD student 1.0 FTE will work in close collaboration with the Theory RF in modelling the experimental implementation of the MPE (**Task 2.1**), as well as in developing alternate heat engines for the ion trap platform (**Task 2.2**). The student will also investigate possible scalability strategies for these systems (**Task 2.3**).

SIGNIFICANCE AND INNOVATION

Significance of research, new technologies and advancing knowledge

The erasure principle underlying the new MPE [5, 7, 8] is at the research forefront in quantum thermodynamics theory [26] and is yet to be realised experimentally. In contrast to current efficiency-constrained heat engines that use energetic degrees of freedom only and produce waste heat as a result, the MPE's use of both energetic and spin (angular momentum) degrees of freedom allow it to operate without waste heat, and thus at maximum energy efficiency. The proof-of-principle demonstration of a MPE will verify the theory and also lay the foundation for a new technology that has the potential to revolutionise the way we harness energy for mobile devices and at remote sites. The proposed theoretical analysis will establish the principles underlying the scalability and robustness of the designs. LMC is the world's largest research and development company and wish to develop commercial applications of the new energy technology explored in this project in the longer term.

Meeting the objectives of the Linkage Projects scheme

- ***Collaborative research between university-based and other sector researchers.*** The project will help build a long-term strategic research collaboration between researchers at Griffith University and Lockheed Martin Corporation (US) and maintain the long-term ($\sim$20 years) research collaboration between CI Vaccaro and PI Barnett (Glasgow University, UK). The long-term goal of the collaboration is to build new energy technologies based on the application of information erasure to thermodynamical systems.
- ***Research training, career opportunities and work with industry and other end-users.*** These collaborations will benefit the Research Fellows, PhD students and Honours students involved in the proposal, enabling them to engage and co-author papers with our internationally-leading PI Barnett FRS, and attend international conferences to present their results and build social networks. It will also enable them to work with engineers and scientists at LMC, which is the world's largest research and development company.
- ***Research in the energy priority area.*** The proposal continues Australia's long-standing activity in undertaking influential research in energy technologies and participating in collaborations with major international institutions.

National Priorities and Challenges

A potential outcome of the proposal is a revolutionary new technology for harnessing and using energy that is not only more efficient than current technologies, but also capable of accessing new energy sources, such as single temperature reservoirs, that are currently inaccessible. This falls under the Science and Research Priority topic of *Energy* and would help Australia meet its Practical Research Challenge to develop *new clean energy sources and storage technologies that are efficient, cost-effective and reliable*.

Commercial Links

An important goal of the project is to give proof-of-principle demonstrations of new kinds of heat engines and establish the thermodynamical framework underpinning their operation and scalability and robustness. This will build a knowledge base for understanding how this new energy technology might be developed in the future and will be of immense benefit to LMC, who wishes to develop commercial applications of the new energy technology explored in this project in the longer term. Indeed, Dr N. Allen, Chief Scientist at LMC, has previously applied for a US patent covering similar technology [27].

APPROACH AND TRAINING

Conceptual framework

In a pilot study [9], done with the support of LMC as part of LP140100797, the CIs developed proposal of an ion trap experiment to demonstrate the working principles of the MPE shown in Fig. 1(b). A cycle of operation of the ion trap implementation consists of three stages: (a) work extraction from a thermal bath; (c) resetting via a low entropy reservoir; and (c) rethermalisation. The vibrational motion of an ion crystal and one of the trapped ions

together represents the working fluid—their states at different points of a cycle are shown in Fig. 2 Top labelled A, B and C. Each ion has two energy-degenerate ground spin states, and is initially in the spin up state $|\uparrow\rangle$.

In the work extraction stage (a), transitions between the two ground spin states are induced by two laser fields far detuned (by Δ) from an upper level in a Λ configuration, as illustrated in Fig. 2 Top A. Laser 1, indicated with the Rabi frequency Ω_1 in the figure, is further detuned by an integer number m of the vibrational frequency ν such that, whenever a transition from $|\uparrow\rangle$ to $|\downarrow\rangle$ happens, $\hbar\delta = m\hbar\nu$ of thermal energy from the mechanical vibration of the ionsconverted into optical work, in the form of a loss of 1 photon from the less energetic coherent field 1 and a gain of 1 photon in the more energetic coherent field 2. At the end of this stage, the ion is found in a mixed state with population split between the $|\uparrow\rangle$ and $|\downarrow\rangle$ states, as illustrated in Fig. 2 Top B.

The resetting stage (b) can be implemented, in principle, by bringing the ions into contact with a bath (buffer gas) of spin-polarised atoms in the $|\uparrow\rangle$ state, shown as blue arrows in Fig. 2B, so that spin-exchange collisions [28] reset the state of the ions back to its initial spin state without energy expenditure as depicted in Fig. 2 Top C. Instead, angular momentum from the spin bath, which works as our entropy capacitor, is consumed in the process.

For the rethermalisation stage (c), the ion crystal is brought in contact with a thermal bath to restore its initial vibrational state. This brings the working-fluid back to the configuration in Fig. 2 Top A, completing the cycle.

The properties of the whole cycle is summarised in Fig. 2 Bottom, where the average number of vibrational quanta, $\overline{n}$, for the A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ A cycle is shown as a function of the spin and motional entropies, S_{spin} and S_{vib}, respectively. This diagram is an extension of the standard temperature versus entropy (TS) diagram for a Carnot heat engine to the case of our MPE which involves two different entropies. Waste heat is avoided because the path B $\rightarrow$ C involves the removal of entropy from the working fluid without changing its energy. In our pilot study, we analysed the behaviour of this cycle for a variety of experimental parameters, in preparation for the experimental part of this proposal, as discussed below.

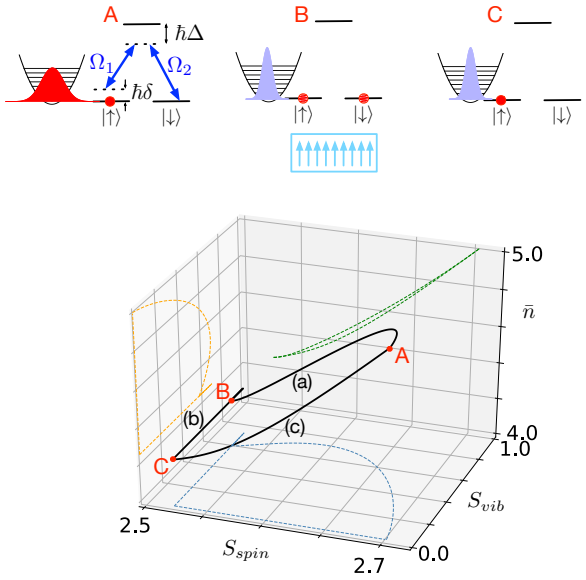

Fig. 2: **Top:** Vibrational and spin states of the ion trap MPE at various points in a cycle. **Bottom:** Average motional quanta $\overline{n}$ in terms of vibrational and spin entropies, S_{vib} and S_{spin}.

Methodology & Research Plan: ***Objective 1 Demonstrate the operation of a MPE experimentally***

- ***Task 1.1: Single step entropy extraction cycle on a single ion.*** We will perform the single-step work extraction (Fig. 2 Top A) on trapped $^{171}Yb^{+}$ using the Griffith supported 370 nm Raman laser system[4]. Differently from the 3-stage idealised model described above, in the experiments, the vibrational modes rethermalise continuously under the influence of the surrounding environment and anharmonic trap interactions. One of the important experimental tasks is to characterise the rethermalisation rate of how quickly the crystal's vibrational modes return to a Maxwell-Boltzmann distribution after a single extraction. We will optimise Raman detunings and laser beam spot sizes to balance speed against fidelity. Note this is similar to Raman cooling protocols for QIP, but different in aim. The "bad" performance limits where defects in the cooling cycle are not important or when we're not as deep in the Lamb-Dicke recoil separated side-band limit may in fact be more fruitful research regimes in investigating per-step entropy extraction efficiency.

- ***Task 1.2: Multiple cycles: using a different ion for each cycle.*** As mentioned in the Conceptual Framework section, the interaction of an ion with a cloud of spin-polarised atoms (Fig. 2-(b)) proposed in our LP14 study [9] would introduce a degree of complexity in the experiment that would make it extremely challenging, if not unrealistic, for the time frame of this proposal. Instead, here we put forward a much simpler alternative based on a chain of ions suitably prepared in state $|\uparrow\rangle$ (see Fig. 3). This chain can be thought as a finite spin reservoir that allows the cycle to be repeated as one applies the Raman pulses sequentially along the chain. Alternatively, one can think that, as the cycle moves from one ion to the next, the working fluid (ion) is constantly being replaced by another one in the original initial state. This process works as an addressable quantum memory, where entropy is removed by repeatedly transferring a phonon mode state into individual quantum memory locations. Experimentally, by spatially steering the 370 nm Raman laser beams using a pair of Acousto-Optic modulators, different ions in the crystal can

[4]The laser is part of a $170k pilot project that is funded by Griffith University.

be addressed and therefore targeted.

Even though this would, ideally, be a simple repetition of **Task 1.1** in a sequence of ions, in our trap different ions in the crystal have different couplings to the collective motional modes. As a consequence, as our cycles move along the array, this has to be taken into account. Theoretically, this will be carefully modelled as part of **Task 2.1** to guide the experimental approach. Experimentally, as a new ion is addressed, either the laser power and/or detuning need to be changed, or we will have to take into account a minor difference for the amount of work extracted in different ions in the chain.

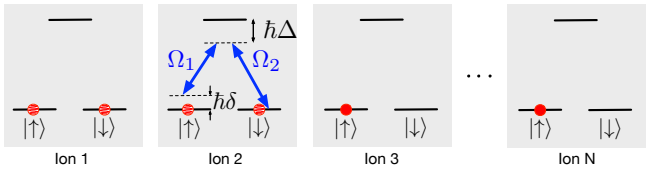

Fig. 3: Chain of ions for implementation of the MPE. The chain works as a pre-prepared spin reservoir and the work cycles are implemented in each ion at a time. Full circles represent the population prepared in state $|1\rangle$ while the striped circles represent the partial populations in states $|\uparrow\rangle$ and $|\downarrow\rangle$ after the work extraction stage (in the figure, ions 1 and 2 have been through the cycle).

- ***Task 1.3: Expansion step: Increase efficiency of entropy extraction.*** The scheme described in the Conceptual Framework section considers an initially thermal motional state for the ion chain. Here we aim at demonstrating that the coherent addition of energy can improve the entropy extraction [9]. This protocol requires sequential application of sideband resolved excitation and stimulated emission, and so we will use an optically excited (411 nm) meta-stable $D_{5/2}$ state with a sufficiently long lifetime (7 ms) to allow coherent, frequency resolved sideband operations. This is the Cirac-Zoller gate as originally proposed, in contrast to modern implementations that use Raman transitions detuned from stronger lines.

- ***Task 1.4: Multiple cycles: entropy concentration in a single ion.*** The number of cycles in the MPE using the ion crystal in **Task 1.2** is limited by the number of ions in the chain. Here, instead, we want to explore the possibility of implementing many cycles using multiple states in a single ion. For that, we will use the meta-stable $D_{5/2}$ state from **Task 1.4**, increasing the number of available states to 12 in two hyperfine levels (F=3,F=2) and accessing further entropy extraction steps through Raman transitions off the 976 nm repump line. These states sit completely outside the state readout protocol of the $S_{1/2} - P_{1/2}$ 370 nm cooling transition and $D_{3/2} - [3/2]_{1/2}$ leakage channel, allowing for high fidelity deterministic state readout. In addition the $D_{5/2}$'s primary decay path (88%) is in to the meta-stable $F_{7/2}$ state, allowing us to separately sequester and investigate the impact of loss processes.

- ***Task 1.5: Energy extraction: measure thermally sourced increase in photon energy.*** While in **Task 1.1** the measurement of the amount of work is obtained indirectly by measuring the different populations of the degenerate (or nearly) ground states, here we aim at demonstrate a direct observation of work extraction. For that we will replace the second laser in Fig.2-(a) by a coupling with a mode of an optical cavity. The cavity mode will act to enhance the 370 nm Raman transition and the photons generated by the engine cycle can then be detected at the cavity output. Even though detailed theoretical calculations are required to provide the exact configuration for the cavity, we don't expect extreme challenging parameters as the step doesn't require the system to be in the strong coupling regime and would more strongly resemble QIP type "bad cavity limit" photon outcoupler cavities.

Methodology & Research Plan: ***Objective 2 Theoretical investigation of MPEs***

- ***Task 2.1: Model the experimental demonstrations in terms of appropriate theory.*** The MPE described in the fConceptual framework section is a high-level theoretical modelling, based on the Hamiltonian for a laser interacting with electronic and motional states of the ion [30], and analysed using a mixture of analytical solution (considering approximations like the adiabatic elimination of upper levels and neglecting decay) and numerical simulations (using our own Python codes and also the Qutip package). For this model, we investigated the optimality of the work extraction stage in terms of initial motional temperature, Lamb-Dicke parameter, as well as the specific sideband addressed by the laser.

In spite of this preliminary work, the modelling requires fine tuning to faithfully represent the experimental setup in this proposal. At first, the inclusion of the detailed level structure, laser power, detunings, motional heating, and decay rates will guide the search for optimal experimental parameter ranges. This ties nicely with the role played by the theory on achieving the experimental **Task 1.2** and **1.4**, and corresponds to the work planned for the 2018/2019 period in the project timeline shown below.

When the first experimental results come out, a second stage of theoretical work will take place. This will consist in supporting the analysis of experimental data, including errors and imperfections not predicted in the original model. This will be done by the PhD student and the RF under the supervision of CIs Carvalho and Vaccaro, which, together with CI Streed, will coordinate the communication between theory and experiment.

- ***Task 2.2: Exploring alternate heat engines.*** In the experiments described in **Aim 1**, heat is converted into optical work. However, a more practical engine would be able to convert heat directly into mechanical work or, even

better, into electricity. Our goal here is to explore ion-trap MPE designs that could achieve this.

Our approach is inspired by a recent work by Rossnagel and collaborators [18]. In their experiment, they used a trap design where changes in motional temperature in the radial plane induce a force on the ion in the axial direction. By alternating the coupling of the ion between a hot and a cold reservoir, they were able to produce a classical single-ion heat engine that outputs mechanical work in the form of oscillations in the axial direction.

In order to transform this into a MPE, we need to be able to replace the cold thermal reservoir by an entropy one not based on energy, in the same spirit of our original engine. The path that we intend to follow is the one of reservoir engineering, an area that CI Carvalho is an expert on [31, 32]. While in [18] the hot reservoir is induced by extra noise in the electrodes superimposed to a cooling mechanism, our idea is to introduce an engineered thermal reservoir [32] that would also introduce transitions between the energy degenerate states of the ions with different spins. This time, instead of generating optical work, the transition would be connected to a spontaneous emission channel and, therefore, consist of exchange of heat between ion vibration and the reservoir. The spin degree of freedom would work as a marker, or memory, that holds information that the exchange happened. Erasing this information using one of the schemes described in **Tasks 1.2** and **1.4** would restore the initial electronic state.

This part of the project will involve the development of these incipient ideas into a solid theoretical model for this type of engine, a task that CI Vaccaro and CI Carvalho have demonstrated ability [8]. It will consist of:

- designing the laser interactions required to create the appropriate engineered reservoir.
- model the full cycle including spin and motional transformations.
- investigate the coupling of motional vibration to antennas to convert mechanical work into electricity.

• ***Task 2.3: establish principles for scalable designs.*** As modern devices require smaller and more powerful batteries, there is a trend towards increasing their energy density. The safety issues resulting from this energy concentration, like higher chance of explosions or fire, could be completely eliminated by entropy-based capacitors. Understanding how much entropy can be stored in a given physical system is therefore of crucial importance, and a top priority for LMC, for the development of practical memory-based devices [27]. The MPE yields energy at the rate of $k_B T \ln(2)$ per bit of entropy stored in the entropy capacitor when operating at temperature T. The entropy capacitor would significantly outperform conventional energy storage sources when its entropy scales super-linearly, i.e. increasing faster than linearly, with the mass. We call this issue the *scalability problem*.

There have been a number of papers discussing ultimate physical limits of entropy density [33–36]. We are interested in practical limits that apply to materials that are available now or could be manufactured in the near future through advances in nanofabrication, etc. There are many ways to approach this problem. Recently, van Dam and Nguyen [37] considered a selection of Hamiltonians, and calculated the minimum value of the product (energy)×(surface area) averaged over the corresponding energy eigenstates for a given entropy. We plan to use a similar approach but focus instead on the maximum entropy that can be stored for fixed values of energy and volume. The entropy will be treated as a functional of the Hamiltonian and we will use variational techniques to find the optimum Hamiltonian that yields the maximum entropy. Other possibilities will also be considered.

An alternative approach is suggested by the nonextensive statistical mechanics [38, 39] introduced by Tsalis. It deals with the fact that many materials and situations exist for which the Gibbs entropy S is nonextensive.[5] In these cases, the Tsalis entropy S_q [39] is useful, where the parameter q determines the level of departure from the Gibbs entropy S, with $S_{q=1} = S$. We plan to evaluate the cost of erasure and the performance of MPEs in cases where the entropy capacitor exhibits nonextensive Gibbs entropy. The Gibbs entropy quantifies the information erased in the Maxwell-demon interpretation of a heat engine, and being nonextensive may give scaling advantages as the size of the system increases, as needed for the scalability problem.

At the practical level, however, most devices work far from such physical limits. This opens up a different kind of question: how does one optimise the memory-powered devices to maximise the rate of entropy exchange? For active erasure mechanisms, i.e. those based on protocols to reset the entropy as the one proposed by CI Vaccaro and PI Barnett [5], our goal is to investigate the design of new time-optimised schemes. Passive erasure processes, on the other hand, are those where the reset occurs thanks to the interaction with a low entropy reservoir. Our aim here is to use quantum control techniques, an area that CI Carvalho has an extensive experience with, in order to design optimal entropic reservoirs. In particular, we want to explore quantum feedback and optimal control theory to manipulate decay rates in both Markovian and non-Markovian reservoirs [40]. In summary, our investigation into the scalability problem for entropy capacitors will consist of:

- analysis of the maximum entropy density for available systems,

[5] An extensive quantity scales linearly with the system size, hence our interest in nonextensive entropy here.

- examining the potential of material with nonextensive Gibbs entropy as an entropy capacitor, and
- engineering entropy capacitors and manipulating them using quantum control techniques.

Research Training

The work planned under Objectives 1 and 2 will provide ideal training in experimental and theoretical physics for two HDR students (one expt, one theory) and a number of Honours students. The experimental work will provide the opportunity to train the students in the the specific practical aspects of operating atomic physics apparatuses and the construction of its various laser, electronic, imaging, and vacuum subcomponents. The modelling of ion traps in different configurations is ideal for developing theoretical and numerical skills. The research will lead to a number of publications in international peer-reviewed journals jointly authored with the students.

Timeline

Aims and objectives	2018-19	2019-20	Expt	Thy	LMC
Aim 1 Demonstrate MPE experimentally					
1.1 Single step extraction			•		
1.2 Multiple cycles: one cycle per ion			•	•	•
1.3 Expansion step & increased efficiency			•		
1.4 Multiple cycles: entropy concentration in 1 ion			•		
1.5 Verify energy extraction			•	•	•
Aim 2 Theoretical investigation of MPEs					
2.1 Model experimental demonstrations			•	•	•
2.2 Explore alternate MPE designs				•	•
2.3 Establish principles of scalable designs				•	•

■ = planned time, ■ = flexibility in start and end points, • = main responsibilities of the investigators, **Expt** = Streed & experimental RF (GU), **Thy** = Carvalho, Vaccaro & theoretical RF (GU), Barnett (U of Glasgow), **LMC** = Uribarri & Allen (PI & PO LMC).

FEASIBILITY

Research Environment

- ***Griffith University*** is a world standard research-intensive university undertaking an array of research activities. It's research centre, the Centre for Quantum Dynamics (CQD), conducts both experimental and theoretical research in quantum information, quantum foundations, quantum optics, nano-scale physics, and AMO physics. The Centre comprises more than 40 researchers, counting continuing academic staff, research fellows, and higher-degree research students, making it well above the "critical mass" for providing a positive and enthusiastic research environment in which to undertake the research in this proposal. It hosts a Node of the ARC Centre of Excellence for Quantum Computation and Communication Technology. Its Australian Attosecond Science Facility is unique in Australia and is a member of the international Max Planck Centre for Attosecond Science. In latest *Excellence in Research Australia* (ERA) round, in 2015, Griffith received the highest rating (5) in both the *physical sciences* in general, and in *quantum physics* in particular—an achievement matched by only six other Australian universities.

- ***Glasgow University*** is ranked 65th in the world by the Quacquarelli Symonds (QS) World University Rankings in 2018. The School of Physics and Astronomy is a vibrant centre of research rated as excellent in the final UK research assessment exercise (RAE2008) with 60% of staff assessed to have research that is "internationally excellent in terms of originality, significance and rigour", and ranked equal with the Physics Department at Imperial College London. In the more recent Research Excellence Framework (REF2014) the College of Science and Engineering, in which the School resides, 90% of research was judged to be 'internationally excellent' or better. When it came to impact, 95% was assessed as having very considerable reach and significance.

- ***Lockheed Martin Corporation.*** As one of the worlds largest technology companies, with annual turnover of $50B, LMC is deeply involved in research and development in a multitude of areas, including aerospace, security and energy storage. It has substantial experience and capacity in all aspects of research and development and has been in a successful research partnership with CI Vaccaro and Griffith University since 2014.

- ***Higher Degrees by Research.*** The Griffith Graduate Research School is the element within the University that has academic oversight and administrative responsibility for all aspects of the HDR candidature. It offers a range of opportunities to enhance the HDR experience including orientation, skills training and works in partnership with CQD and other University Offices to coordinate HDR activities and monitor the provision of research support and facilities. The University defines a minimum standard of resources available to HDR students including office space, computer equipment, and financial assistance to attend conferences.

- ***Established trapped ion laboratory.*** Griffith has invested $120k for the purchase of a tunable MSquared SolTiS ECD-X laser operating at 370 nm as part of the seed funding for this project to establish operational Raman

cooling. This integrates with Griffith's existing Yb^+ trapped ion facilities.

- ***Overall feasibility.*** The project has been designed with the expertise and availability of the CIs and PIs, as outlined in the section INVESTIGATORS, and the currently available lab equipment[6] in mind. The funding requested for an Experimental Research Fellow along with CI Streed's 0.5 FTE will provide 1.5 FTE to this project. The equipment requested compliments that supported by LMC to enable each of the experimental Tasks 1.1 - 1.5 to be performed, as detailed in section F Budget Justification. **Timeline** above. The in-kind contributions from CI Carvalho at 0.4 FTE, PI Barnett at 0.1 FTE, CI Vaccaro at 0.3 FTE, and a theoretician RF at 1.0 FTE will bring the total theoretical effort to 1.7 FTE persons over 2 years, which is sufficient to perform Tasks 2.1 - 2.3, given the success of previous research projects, and Linkage Project LP140100797 in particular.

Evidence of Partner Organisation's commitment

- ***Evidence of Commitment.*** LMC is a global security and aerospace company which is also engaged in emerging technologies, such as nanotechnology, for new energy storage systems. Its commitment is evidenced through previously partnering with CI Vaccaro on ARC Linkage Project LP140100797, the theory-focused Linkage Project that led to this proposal. It is involved in this proposal through its funding to Griffith University of $483k, and by providing intellectual input into all parts of the project through PI Uribarri and Chief Scientist Ned Allen, and for assistance in application development, technology transfer and protection of intellectual property. LMC will benefit from the deeper understanding of energy storage systems provided by the basic research undertaken in this project. This projects entails the demonstration of proof-of-principle of new kinds of heat engine as well as developing the supporting theory as the first steps towards the longer-term goal of generating new energy technology. The development that is needed to bring the technology to practical realisation is set to forge a long term alliance between LMC and Griffith University.
- ***Cash and in-kind Contributions.*** LMC is contributing a total of $483k in Cash, primarily as teaching relief ($198k) for CIs Streed ($106k) and Vaccaro ($92k), as well towards equipment ($194k), with an additional $120k in-kind for the engagement of LMC affiliated personnel ($100k) and travel ($20k) costs. The project will support 2 PhD students, one of which will funded by GU with $54k in Cash over 2 years. LMC's equipment contribution 68% of the budget and is focused on laser equipment.

The total cost of travel for the Australian project is $50k of which $30k is being requested from the ARC. The remaining $20k will be covered by LMC in Cash with another $20k in-kind for travel costs related to LMC personnel. The total Cash contribution of $483k by LMC is therefore adequate for the project. The In-kind contribution from LMC entails contribution from PI Uribarri 0.05 FTE, Chief Scientist Allen 0.05FTE and a Technical Assistant 0.05 FTE at a total in-kind cost of $100k. LMC provided a similar commitment for the previous Linkage Project LP140100797. The success of that project (see progress statement in section G2 for details) indicates that LMC's In-kind contribution is also adequate for this project.

BENEFIT

Strategic research alliances & benefits for Partner Organization

The goal of the project is to implement proof-of-principle demonstrations of new kinds of heat engines and develop supporting theory. The outcomes will inform future planning of an ongoing R & D alliance between LMC and Griffith University for the purpose of developing this new energy technology to commercial applications, and maintain the research alliance between the University of Glasgow and Griffith University.

Potential for economic and commercial benefit to Australia

The Collaboration Agreement between LMC and Griffith University for LP140100797 agreed to IP rights being owned by the respective organisation responsible for their creation. The same terms will be negotiated for the current LP. LMC has a long-standing track record of bringing fundamental physics developments to widely deployed functioning systems, examples including Stealth and GPS technologies. Partnering with LMC will allow us to access technologists with experience in maturing prototype proof-of-principle systems. The project cost of $635k in Australian public funding (ARC+GU Cash) and $483k in foreign commercial funding (LMC Cash) represents an internationally-leading research project being performed in Australian at a 57% discount to Australia's public purse.[7] Moreover, the project has potential for Australia to take a leading position in the development of economically-disruptive energy technology; the monetary value of the economic benefits of this would far exceed the cost in public funding many times over. All this clearly demonstrates the Project as being **exceptionally good value for money**.

[6] Including a 370 nm Raman laser system that is part of a $170k pilot project funded by Griffith University.

[7] If Cash and In kind are included, the figures are $849k of Australian public funding and $603k in foreign commercial funding representing the project at a 58% discount to Australia.

COMMUNICATION OF RESULTS

We plan to disseminate our results in three main ways. The first is by reporting in international peer-reviewed journals. We intend to publish the most significant results in leading journals including Nature, Science, Nature Physics, Physical Review Letters and publish other important work in journals such as Physical Review A, Proceedings of the Royal Society A, Optics Express, and New Journal of Physics, as we have in the past. Next is through presentations at conferences and workshops both international (e.g. DAMOP, ICAP, CLEO, Photonics West) and domestic (e.g. AIP Congress, ANZCOP, Quantum Technologies Workshops). The last is by promoting our research results to a broader public audience through our Marketing and Engagement Office using press releases, media engagement (both traditional and social), and outreach programs to high school students.

MANAGEMENT OF DATA

Data generated in this project will be stored locally at Griffith using personal computers. When possible, publications arising from this research will include the full supporting data set to facilitate reproduction of results as part of the supplemental data hosted on publisher websites. Data from this project will also be accessible via Griffith's Research Data Repository, a publicly searchable database that is registered in the national Research Data Australia catalogue. Students and RFs will also retain personal copies of a full set of data for their associated research activity.

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C2. List the objectives of your proposed Project

(List each objective separately by clicking 'add answer' to add the next objective. You may enter 500 characters (approximately 70 words) per objective.
This information will be used for future reporting purposes if this Proposal is funded.
(This question must be answered))

Objective

Demonstrate the operation of a memory-powered engine experimentally

Objective

Investigate memory-powered engines theoretically

C3. Medical Research

(Does this Project contain content which requires a statement to demonstrate that it complies with the eligible research requirements set out in the ARC Medical Research Policy located on the ARC website?)

No

C4. Medical Research Statement

(If applicable, in no more than 750 characters (approximately 100 words), justify why this Project complies with the eligible research requirements set out in the ARC Medical Research Policy located on the ARC website. Eligibility will be based solely on the information contained in this Proposal. This is your only chance to provide justification, the ARC will not be writing to seek further clarification.)

Part D - Personnel and ROPE (Dr Erik Streed)

D1. Personal Details

(To update personal details, click the 'Manage Personal Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Participation Type

Chief Investigator

Title

Dr

First Name

Erik

Second Name

William

Family Name

Streed

D4. Qualifications

(To update any qualifications, click on the 'Manage Qualifications' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Conferral Date	AQF Level	Degree/Award Title	Discipline/Field	Awarding Organisation	Country of Award
06/02/2006	Doctoral Degree	Doctor of Philosphy	Physics	Massachusetts Institute of Technology	United States of America
11/06/1999	Bachelor Degree	Bachelors of Science	Physics	California Institute of Technology	United States of America

D5. Research Opportunity and Performance Evidence (ROPE) - Current and previous appointment(s) / position(s) - during the past 10 years

(To update any details in this table, click on the 'Manage Employment Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile. Refer to the Instructions to Applicants for more information.)

Description	Department	Contract Type	Employment Type	Start Date	End Date	Organisation
Senior Lecturer in Physics	School of Environment and Natural Science	Permanent	Full Time	02/01/2018		Griffith University
ARC Future Fellow	Institute for Glycomics/School of Natural Sciences	Contract	Full Time	02/01/2014	02/01/2018	Griffith University
Senior Lecturer in Physics	Biomolecular and Physical Science	Permanent	Full Time	25/09/2013	02/01/2014	Griffith University
Lecturer in Physics	Biomolecular and Physical Science	Permanent	Full Time	01/03/2011	25/09/2013	Griffith University

Research Fellow 2	Biomolecular and Physical Sciences	Contract	Full Time	01/01/2011	01/03/2011	Griffith University
ARC Australian Postdoctoral Fellow	Biomolecular and Physical Science	Contract	Full Time	01/01/2008	01/01/2011	Griffith University
Research Fellow, Level B	Biomolecular and Physical Science	Contract	Full Time	01/04/2007	01/01/2008	Griffith University

D6. Research Opportunity and Performance Evidence (ROPE) - Academic Interruptions

(You must read the ROPE Statement http://www.arc.gov.au/arc-research-opportunity-and-performance-evidence-rope-statement before filling out this section.)
Have you experienced an interruption that has impacted on your academic record?

No

D7. Research Opportunity and Performance Evidence (ROPE) - Details of your academic career and opportunities for research, evidence of research impact and contributions to the field, including those most relevant to this Proposal

(Upload a PDF of no more than five A4 pages with details of your academic career and opportunities, evidence of research impact and contributions to the field.)

Uploaded PDF file follows on next page.

D7. Research Opportunity and Performance Evidence (ROPE) - Career, opportunities and impact and impact - CI Streed

AMOUNT OF TIME AS AN ACTIVE RESEARCHER

I was awarded my PhD in Physics 12 years ago in February 2006 and graduated in June of 2006. I have experienced no periods of academic interruption.

RESEARCH OPPORTUNITIES

Academic interruptions

None

Employment situation

Senior Lecturer in Physics School of Environment and Natural Science, Griffith University Balanced load academic with 40% teaching and 20% service profile.	Jan 2018-present	**0.4 FTE research**
ARC Future Fellow Institute for Glycomics, Griffith University Teaching and service contributions of 0.1 FTE as a result of being the only physics faculty with an office on the Gold Coast campus. Acquired Kielpinski Ion trapping lab at Nathan campus July 2016 upon his departure.	Jan 2014- Jan 2018	**0.9 FTE research**
Senior Lecturer in Physics School of Biomolecular and Physical Science, Griffith University Balanced load academic with 40% teaching and 20% service profile.	Sept 2013- Dec 2013	**0.4 FTE research**
Lecturer in Physics School of Biomolecular and Physical Science, Griffith University Started on the Gold Coast campus with no existing physics faculty, physics BSc program, or physics laboratory infrastructure. Balanced load academic with 40% teaching and 20% service profile.	Mar 2011- Sept 2013	**0.4 FTE research**
Research Fellow 2 School of Biomolecular and Physical Sciences, Griffith University Bridging postdoc to start of continuing position.	Jan 2011-Mar 2011	**1.0 FTE research**
ARC Australian Postdoctoral Fellow School of Biomolecular and Physical Science, Griffith University Supported by ARC DP to work on Fresnel lenses in CQD ion trapping lab.	Jan 2008- Dec 2012	**1.0 FTE research**
Research Fellow, Level B School of Biomolecular and Physical Science, Griffith University Continuing work in CQD Ion Trapping lab with Dave Kielpinski.	Apr 2007-Dec 2007	**1.0 FTE research**
Research Fellow, Level A School of Science, Griffith University Co-founded Griffith Centre for Quantum Dynamics Ion trapping lab with Dave Kielpinski. Moved apparatus from MIT to Nathan campus.	Jan 2006- Apr 2007	**1.0 FTE research**

Current Roles

My position has a standard academic profile of 0.4 FTE research, 0.4 FTE teaching and 0.2 FTE service.

In my 0.4 FTE research role I direct the activities of the Ion Trap lab of the Integrated Quantum Technologies Group at the Nathan campus (1 postdoc, 3 PhD students) as well as the biophysics lab at the Gold Coast campus (2 undergraduates) and projects in Fresnel lens fabrication (US Army) and collaborations in Geophotonics (1 PhD student near completion) and materials science. The bulk of this time is presently focused on the ion trap lab with a secondary on the biophysics lab.

As part of my 0.4 FTE teaching I convene 3rd year Physics Lab, 2nd year Calculus 2 (¿250 students), and first year Physics 1B on the Gold Coast. I also teach into 3rd year Quantum Physics, 2nd year Classical and Quantum Physics.

My 0.2 FTE service fraction involve internal university and physics community committee work, public outreach both on campus and in the community, and academic service as peer reviewer of both journal articles and PhD theses, editorial duties for Scientific Reports. I also run a Gold Coast based summer undergraduate lab experience program during the summer break period.

Research mentoring and facilities

Griffith University offers research mentoring by a senior research academics as part of its Academic Staff Career Development Procedures document number 2017/0000505. When the need arises, I consult with fellow Centre for Quantum dynamics members Prof. Howard Wiseman FAA, Prof. Geoff Pryde, and former member Prof. David Kielpinski. During my ARC Future Fellowship I was directly mentored by Institute for Glycomics head Prof. Mark von Itzstein FRACI.

The Griffith Centre for Quantum Dynamics has a wide variety of shared specialty electronic, optical, and vacuum equipment which are critical to the setup and debugging of quantum physics experiments. These include diagnostics such as RF spectrum analyzers, high-speed oscilloscopes, spectrometers, and optical spectrum analysers. Vacuum hardware available includes a Helium leak detector, roughing and turbomolecular pumps for UHV chamber prep., residual gas analysers, heater tapes, band heaters, and their associated control electronics. Specifically for this project there is the established Yb^+ ion trapping lab which I co-founded with Dave Kielpinski upon our arrival from MIT in 2006. This includes an ion chip trap type apparatus with integrated diffraction mirrors intended for use with this research proposal as well as a needle trap type apparatus with integrated phase Fresnel lens which was constructed during my APD.

RESEARCH ACHIEVEMENTS AND CONTRIBUTIONS

Invited keynote and speaker addresses (last 10 years) * relevant to this application

1 **Keynote speaker,**
Griffith University Cutting Edge STEM secondary teachers workshop. “A single atoms shadow Groundbreaking research producing the worlds first photograph of a single atoms shadow” 4 December 2012. Approx. 200 SE Qld secondary science and maths teachers.

2 **Invited speaker,**
2015 Australian Institute of Physics-Queensland Branch John Mainstone Youth Lecturer. Talks in Mt. Isa, Brisbane, Hervey Bay, Sunshine Coast, Cairns, Townsville, and Toowoomba. Total audience est. 250-300 Year 11-12 Physics students. Various dates July-August 2015.

* 3 **Invited speaker,**
“Quantum Engines that run off Information” Colloquium Talk at Macquaire University Sept 12, 2017

* 4 **Invited speaker,**
CSIRO Pint of Science- ”Quintessential Quantum Physics” Parkwood Tavern, Gold Coast, May 15, 2018.

70 paying members of the public. Promotional interview on ABC Coast FM played afternoon of May 15th, replayed morning May 16th. Front page photo and article in Gold Coast Bulletin May 16th.

✻ 5 **Invited speaker,**
UQ Quantum Science Seminar at University of Queensland *scheduled June 5, 2018*

Research support income (last 10 years)

Internal Grants

$20,000 2011 School of Biomolecular and Physical Sciences Teaching & Learning Grant - "Undergraduate and High-school charge particle trap demonstrator apparatus"
$80,000 2012 Griffith University Research Infrastructure Program "Establishment of the Joint Laboratory for Quantum Molecular Biophysics" Laboratory startup equipment funds.
$225,000 2012 Physical Science Area of Strategic Interest "Establishment of the Joint Laboratory for Quantum Molecular Biophysics" Laboratory Renovation funds.
$95,000 2013 Griffith University Research Infrastructure Program "Single Molecule and FRET Microscopy"
$20,000 2013 Griffith Teaching & Learning Grants "Summer Research Fellowships in SEET- a sustainable model for undergraduate research and a pipeline for future Honours and HDR students"
$132,000 2018 Griffith Sciences Equipment Fund Grant "Physical Sciences Diagnostic Suite"

National Competitive Grants Awarded

✻ **$520,000** 2008-2010 ARC Discovery Project and Australian Postdoctoral Fellowship DP0877936 "A Photonic Interconnect for Trapped Ion Quantum Computing"

$756,000 2013-2017 ARC Future Fellowship FT130100472 "Trapped Ion Imaging for Biomolecular Dynamics"

National Competitive Grants Held

These are grants which I was added onto after their award due to personnel changes.

✻ **$396,00** 2013-2016 ARC Discovery Project DP130101613 "Building Schrödinger's cat: large-scale entanglement of trapped ions"- Replaced Lead CI David Kielpinski who departed Australia for family reasons. Sole experimental CI.

✻ **$749,409** 2014-2017 ARC Linkage Project LP140100797 "Lightweight battery with more yield than a tonne of coal", Replaced Experimental PI Kimberly Hall of Dalhousie University, Canada with change of focus for experimental realisation from implementation in Quantum Dots to trapped ions.

International Grants

$50,000 USD 2009 US Air Force- Asian Office for Research and Development "Laser Stabilization for Doppler LIDAR of the Ionosphere"
$46,239 USD 2017 US Army Research, Development, and Engineering Command International Technology Centre-Pacific "Quantum Device Photonic Interconnects"

Awards

2010 InnoCentive InnoCentive Challenge #8509721: "Technologies for High Throughput Quantification of Nanoparticles." **Cash Prize of $20,000 USD & sale of intellectual property.**
2011 Queensland Young Tall Poppy Science Award- **presented by Queensland Premier** Anna Bligh at Parliament House.
2013 Conference on Lasers and Electro-Optics/Pacific Rim Best paper Award for "Imaging a Single Atom's Absorption and Phase Shift" **Cash Prize of ¥20,000 (equiv $200)**

Patents

Provisional Patent: 2001902245 "Optically generated Switchable Frequency Phase Locked Microwave Source"- *lapsed*

Identifiable benefits outside of academia

My work on the Nature Communications publication "Absorption imaging of a single atom" resulted in **extensive international media coverage** in both in science specific venues and general news. This included the homepages of Science.org, Nature.com, National Geographic, Google News, NBC (USA), CNN.com, UK Daily Mail, Cracked.com, FARK.com, COSMOS Magazine, News.com.au, ABC News, slashdot.org, The Register (UK), ZDNet (US), Deccan Herald (India), Korea Times, Huffington Post, Discover Magazine, and the Metro UK London newspaper. Broadcast media coverage included radio interviews on ABC Brisbane, Gold Coast, and Melbourne's morning programs as well as television segments on "Totally Wild" and an interview on Ten Network's evening news. My popular science commentary article "Snapping an atoms shadow? Now thats a first" on TheConversation.com had received **26,332 reads**. It was also the subject of a Periodic Videos by Sir Martyn Poliakoff FRS of the University of Nottingham with **193,923 views on YouTube**.

As a result of my research mentorship of undergraduate physics student and Olympic swimmer **Cameron McEvoy** I have been featured on ABC News specials and the Seven Network Commonwealth Games Special (repeated aired). Cam has previously participated in my summer undergraduate lab experience program and worked under my direction on independent research projects within the structure of his part-time BSc Honours Physics & Applied Mathematics program.

Other professional activities

Editor, Scientific Reports (Nature Publishing Group)
Thesis reviewer for the Australian National University
Grant Reviewer for the Austrian, Australian, and Romanian government national scientific funding boards.
Peer reviewer for Physical Review Letters, Nature Communications, Physical Review A, Applied Physics Letters, Optics Express, Journal of the Optical Society of America B, and Review of Scientific Instruments.

Describe how your research has led to a significant change or advance of knowledge in your field, and outline how your achievements will contribute to this Proposal.

The significance of my work is in advancing trapped ion quantum information processing (QIP) technology towards practical, large-scale systems [21] and the potential outgrowths from the core technology of good control over quantum systems. My primary impact has been the proposal and successful demonstration of diffractive optics as an efficient, scalable solution to interfacing atoms and photons [12-14,17-18, 21,23,25]. This has had secondary benefits in demonstrating fundamental optical effects associated with a single atom including absorption [17] and phase shifting [18] as well as conversely using the optical signature from single atom as a sensor for temperature [15] and force measurement [28].

Quantum thermodynamics is a natural progression of these developments to probe the behaviour of single atoms, expanding out to larger numbers of atoms and controllably coupling the internal and external degrees of freedom through QIP techniques. Many of our control techniques and all of our detection techniques in trapped ion QIP rely upon optical manipulation of atoms. These achievements demonstrate how I've successfully extended trapped ion QIP technology to make leading contributions on an international level to the interaction of light with single atoms. The ambition of this proposal is tempered by our existing international reputation to making novel contributions as well as the ready reproducibility which the trapped ion QIP provides via numerous other international high-profile groups.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications

i. Publication context and contribution: Upload a PDF of no more than two pages. Provide clear information that explains the contribution and significance of your publications within the context of your discipline/s. This may include the importance/esteem of specific journals in your field; specific indicators of recognition within your field such as first authorship/citations.

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D8. Research Opportunity and Performance Evidence (ROPE) - Publications - CI Streed

i. Publication context and contribution

References marked [NN] refer to publication NN in **D8 ROPE List of publications** that follows.
Citation data are from ISI Web of Science.

My publication record can be segmented time-wise into three periods. Summer undergraduate work at Caltech in which I assisted experienced researchers with discrete contributions [1-2]. Working as a graduate student of Wolfgang Ketterle (Nobel 2001) at MIT to construct [7] the largest atom number ^{87}Rb Bose-Einstein condensate machine and investigate ultracold and quantum phenomena [3-9]. Ion trapping work at Griffith University focused on quantum information processing, diffractive fresnel optics, and the physics enabled by extremely good single atom imaging.

Citation Metrics

Source: ISI Web of Science (ResearcherID: B-4682-2015, ORCID: 0000-0001-6234-4560)

h-index **14**
total citations **1059**

Source: Google scholar (https://scholar.google.com.au/citations?user=ajeoFYMAAAAJ&hl=en&oi=ao)

h-index **15**
total citations **1806**

Imaging single atoms

My greatest impact scientifically has been in what we can learn from imaging single atoms. My pioneering work in integrating microfabricated diffractive optics (proposed [29,12], demonstrated [13], and discussed below) with ion traps enabled the imaging of a single atom with wavelength-scale resolution [14, 21 citations]. This was the starting point to my most widely noted **first author paper in Nature Communications** paper [17] demonstrating the first imaging of a single atom's shadow. While having 25 citations, this paper resulted in substantial domestic and international media coverage, detailed more extensively in *D7 Identifiable benefits outside of academia* including a popular science article [30] I authored in The Conversation with **26,332 reads** and a video with **193,923 views on YouTube**. In analysing the anomalies from this result were subsequently able to use an interferometric technique demonstrate that an atom shifts the phase of the incident light at the radian level [18, Physical Review Letters, 11 citations]. Most recently (2018) I lead the team to mature this imaging technology to realise nanometer scale super-resolution imaging **last author paper in Science Advances** and used it to demonstrate a single atom force sensor with sub-attoNewton sensitivity, capable of **directly observing the positional shift induced by the scattering force** from laser cooling a single atom. These technologies also enable my push into biophysics and geophotonics.

Quantum Information Processing

A primary focus post-PhD has been in Quantum Information Processing (QIP) with trapped ions. In my **first author paper** [12, 15 cites] and conference proceeding [29, 7 cites] I was the first to propose using diffractive optics as a scalable solution to the optical interfacing problem in trapped ion QIP. This was followed by my **first author paper** in Physical Review Letters [12] **successfully demonstrating imaging of an ion with collection efficiency suitable for QIP**. This paper has received **52 citations** indicating the widespread interest in the potential of this technology.

I have lead the trapped ion team further down the scalability path for QIP with my **2017 last author paper** [25] in **Nature Partner Journal Quantum Information** on integrating diffractive mirrors with microfabricated chip trap technology and demonstrating leading coupling into a single mode fibre for Quantum Networking applications. This paper has already received **5 citations**, likewise indicative of the QIP community's interest in this technology's potential, and is the basis for our Australian DST Quantum Technology Program Quantum Router grant proposal. This work complements my contributions towards theoretical

work in integrated architecture for trapped ion QIP [21, 2 citations] with modelling of coupling dipole radiation patterns into various single mode guided structures. I've also contributed to recent (2016) papers in Optics Express [22, 2 cites] UV pulsed laser technology for implementing fast quantum gates and J Optics [23, 3 cites] in UV to telecom IR photon conversion.

Amplification of Matter waves

An early interest in Bose-Einstein condensates was investigation of different approaches to amplification matter-waves as a precursor to use in high-precision matter-wave based sensors. In addition to being substantially involved in the apparatus construction detailed above [7] I contributed to the data taking, analysis, and modelling of investigations in amplification onset [3], Raman amplification [4], and parametric amplification [6]. This resulted in works in **Science, Phys Rev Letters, and Phys Rev A** with **146, 53, and 67 citations**.

Quantum Physics

My thesis topic was the demonstration of the Quantum Zeno effect [8] using both pulsed and continuous measurement techniques, realising a suppression of a factor of 200×. This was my first **first author paper** and has been **cited 97 times** due to its importance both as a fundamental demonstration of the power of quantum measurement and for its implications to reducing decoherence when observing quantum systems. **This work is particularly relevant to the long-term goals of this grant in that efficient preservation of the coherence of erased quantum memories is vital to the practicality of any implementation.** Also in the vein of fundamental quantum physics I contributed modelling and data taking to a paper [5, 107 citations] which answered a fundamental question about the recoil momentum behaviour of a photon in a dielectric medium.

My work in microsphere optical resonators [2] was in support of experimental atomic physics work in creating strong atom-photon coupling through the use of low loss, high finesse optical cavities in the group of H Jeff Kimble at Caltech. As an undergraduate I independently performed the AFM surface roughness measurements, as well as assisting in the apparatus construction, device fabrication, and data taking . This is my most highly cited paper with **317 citations** which was a result of it for many years being the highest quality solid state optical resonator documented in literature.

With the high resolution single atom imaging, I provided in-lab supervision of Ben Norton's experiments into measuring the temperature of trapped ions through imaging [15, 7 citations]. I contributed data to this paper on how laser cooling fails in ion traps when the cooling beam looses Doppler sensitivity. This previous accomplishment in **trapped ion thermometry** further supports my qualifications to extending our work into the more ambitious area of Quantum Thermodynamics.

Scientific Apparatus, Atomic Spectroscopy, & associated support papers

As an experimental physicist I contribute to the design and construction scientific apparatus to perform experiments and the associated supporting technology [7,9,10,11,16,20]. The most important of these was a **first author paper** [7] detailing the construction of Ketterle's shared design ^{23}Na and ^{87}Rb Bose-Einstein condensate machines. This article's **58 citations** is far above Review of Scientific Instruments Impact Factor of 1.5, and likely understates its impact as a **crucial "how-to" paper** of methods, techniques, protocols, and characteristic data. Likewise as a practical matter of working with Yb^+ I have contributed to the literature on Atomic Discharge Spectroscopy [11,16] with **my first author work with 16 citations** [11] on frequency stabilisation resulting in a **US$50k US Air Force grant.**

Multi-disciplinary work

I have applied my optical expertise into the area of biophotonics [19] as well as in collaboration with colleagues in Environmental [24] and Materials Sciences [26,27]. Most notable The geophonics result [24] represents a substantial technical advance in the sensitive of the optical dating technique for buried quartz sediments, which was the result of my approaching the problem from the perspective of quantum efficiency and photon gathering from a dim source.

ii. Publication list: Upload a PDF of no more than five pages. List your publications most relevant to this proposal categorised under the following headings: Authored books; Edited books; Book chapters; Referred Journal articles; Fully refereed conference proceedings; Other publication outputs. CVs and theses should not be included in this list. Next to each, provide the Project ID and years funded for any ARC grant on which you were a CI or Fellow from which the item originated.

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D8. Research Opportunity and Performance Evidence (ROPE) - List of publications - CI Streed

ii. Publications List

Authored books- n/a

Edited books- n/a

Book chapters- n/a

Refereed Journal articles

[1] F Gregoire, SH Wei, **EW Streed**, KA Brameld, D Fort, LJ Hanely, JD Walls, WA Goddard, JD Roberts
"Conformational equilibria of beta-alanine and related compounds as studied by NMR spectroscopy"
Journal of the American Chemical Society **120** 7537-7543 (1998)

[2] DW Vernooy, VS Ilchenko, H Mabuchi, **EW Streed,** HJ Kimble
"High-Q Measurements of Fused-Silica Microspheres in the Near Infrared"
Optics Letters **23** 247-249 (1998)

[3] D Schneble, Y Torii, M Boyd, **EW Streed**, DE Pritchard, W Ketterle
"The Onset of Matter-Wave Amplification in a Superradiant Bose-Einstein Condensate"
Science **300** 475-478 (2003)

[4] D Schneble, GK Campbell, **EW Streed**, M Boyd, DE Pritchard, W Ketterle
"Raman Amplification of Matter Waves"
Physical Review A **69** 041601(R) (2004)

[5] GK Campbell, AE Leanhardt, J Mun, M Boyd, **EW Streed**, W Ketterle, DE Pritchard
"Photon Recoil Momentum in Dispersive Media"
Physical Review Letters **94**, 170403 (2005)

[6] GK Campbell, J Mun, M Boyd, **EW Streed**, W Ketterle, DE Pritchard
"Parametric Amplification of Scattered Atom Pairs"
Physical Review Letters **96**, 020406 (2006)

[7] **EW Streed**, AP Chikkatur, TL Gustavson, M Boyd, Y Torii, D Schneble, GK Campbell, DE Pritchard, W Ketterle
"Large Atom Number Bose-Einstein Condensate Machines"
Review of Scientific Instruments **77** 023106 (2006)

[8] **EW Streed**, J Mun, M Boyd, GK Campbell, P Medley, W Ketterle, DE Pritchard
"Continuous and Pulsed Quantum Zeno Effect"
Physical Review Letters **97**, 260402 (2006)

[9] M Boyd, **EW Streed**, P Medley, GK Campbell, J Mun, W Ketterle, DE Pritchard
"Atom trapping with a thin magnetic film"
Physical Review A **76** 043624 (2007)

[10]JJ Chapman, BG Norton, **EW Streed**, D Kielpinski
"An automated submicron beam profiler for characterization of high numerical aperture optics"
Review of Scientific Instruments **79** 095106 (2008)

[11]**EW Streed**, TJ Weinhold, **D Kielpinski**
"Frequency stabilization of an ultraviolet laser to ions in a discharge"
Applied Physics Letters **93** 071103 (2008)

[12]**EW Streed**, BG Norton, D Kielpinski
"Scalable, efficient ion-photon coupling with phase Fresnel lenses for large-scale quantum comput-

ing"
Quantum Information and Computation **9** 0203-0214 (2009)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[13]**EW Streed**, BG Norton, A Jechow, TJ Weinhold, D Kielpinski
"Imaging trapped ions with a microfabricated lens for quantum information processing"
Physical Review Letters **106**, 010502 (2011)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[14]A Jechow, **EW Streed**, BG Norton, MJ Petrasiunas, D Kielpinski
"Wavelength-scale imaging of trapped ions using a phase Fresnel lens"
Optics Letters **36** 1371-1373 (2011)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[15]BG Norton, **EW Streed**, A Jechow, D Kielpinski
"Millikelvin Spatial Thermometry of Trapped Ions"
New Journal of Physics **13** 113022 (2011)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[16]MJ Petrasiunas, **EW Streed**, TJ Weinhold, BG Norton, D Kielpinski
"Optogalvanic Spectroscopy of Metastable States in Yb^{+}"
Applied Physics B **107** 881 (2012)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[17]**EW Streed**, A Jechow, BG Norton, D Kielpinski
"Absorption imaging of a single atom"
Nature Communications **3** 933 (2012)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[18]A Jechow, BG Norton, S Handel, V Blūms, **EW Streed**, D Kielpinski
"Controllable Optical Phase Shift Over One Radian from a Single Isolated Atom"
Physical Review Letters **110** 113605 (2013)
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[19]MJ Petrasiunas, JBO Wood, D Kielpinski, **EW Streed**
"Three-photon excitation of quantum dots with a telecom-band ultrafast fiber laser"
Applied Physics B **117** 1035-1039 (2014)

[20]B Haylock, F Lenzini, S Kasture, P Fisher, **EW Streed**, M Lobino
"Nine-channel mid-power bipolar pulse generator based on a field programmable gate array"
Review of Scientific Instruments **87** 054709 (2016)
[ARC FT130100472 2014-2017]

[21]D Kielpinski, C Volin, **EW Streed**, F Lenzini, M Lobino
"Integrated optics architecture for trapped-ion quantum information processing"
Quantum Information Processing **15** 5315-5338 (2016)
[ARC FT130100472 2014-2017]
[ARC DP130101613 2014-2016]

[22] MI Hussain, MJ Petrasiunas, CDB Bentley, RL Taylor, ARR Carvalho, JJ Hope, **EW Streed**, M Lobino, D Kielpinski
"Ultrafast, high repetition rate, ultraviolet, fiber-laser-based source: application towards Yb^{+} fast quantum-logic"
Optics Express **24** 16638-16648 (2016)
[ARC FT130100472 2014-2017]
[ARC DP130101613 2014-2016]

[23]S Kasture, F Lenzini, B Haylock, A Boes, A Mitchell, **EW Streed**, M Lobino

"Frequency conversion between UV and telecom wavelengths in a lithium niobate waveguide for quantum communication with Yb^+ trapped ions"
Journal of Optics **18** 104007 (2016)
[ARC FT130100472 2014-2017]
[ARC DP130101613 2014-2016]

[24]DK Borombovits, **EW Streed**, TJ Pietsch, JM Olley
"Spectral signature of single-grain quartz using a high-sensitivity TL imaging system"
Radiation Measurements **95** 1-8 (2016)
[ARC FT130100472 2014-2017]

[25]M Ghadimi, V Blūms, BG Norton, PM Fisher, SC Connell, JM Amini, C Volin, H Hayden, C-S Pai, D Kielpinski, M Lobino, **EW Streed**
"Scalable ion-photon quantum interface based on integrated diffractive mirrors"
Nature Partner Journal Quantum Information **3**, 4 (2017)
[ARC FT130100472 2014-2017]
[ARC DP130101613 2014-2016]

[26]AR Md Foisal, A Qamar, H-P Phan, T Dinh, K-N Tuan, P Tanner, **EW Streed**, DV Dao
"Pushing the Limits of Piezoresistive Effect by Optomechanical Coupling in 3C-SiC/Si Heterostructure"
ACS Applied Materials and Interfaces **9** 3992139925 (2017)
[ARC FT130100472 2014-2017]

[27]Z Wan, **EW Streed**, M Lobino, S Wang, RT Sang, IS Cole, DV Thiel, Q Li
"Laser reduced graphene: synthesis, Properties, and Applications"
Advanced Materials Technologies Online Preview Art. 1700315 (2018)
[ARC FT130100472 2014-2017]

[28]V Blūms, M Piotrowski, MI Hussain, BG Norton, SC Connell, S Gensemer, M Lobino, **EW Streed**
"A single-atom 3D sub-attonewton force sensor"
Science Advances **4** eaao4453 (2018)
[ARC DP130101613 2014-2016]
[ARC FT130100472 2014-2017]

Fully refereed conference proceedings

[29]AA Cruz-Cabrera, SA Kemme, JR Wendt, D Kielpinski, **EW Streed**, TR Carter, S Samora
"High Efficiency DOEs at Large Diffraction Angles for Quantum Information and Computing Architectures"
Proceedings of the International Society for Optical Engineering (SPIE) **6482** 648209, (2007)

Other publication outputs

[30]**E Streed** Analysis piece in the Science+Technology section of The Conversation
"Snapping an atoms shadow? Now thats a first" July 4, 2012
https://theconversation.com/snapping-an-atoms-shadow-now-thats-a-first-8057
[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs

(Upload a PDF of no more than three A4 pages with a list of your ten career-best academic research outputs related to the Proposal.)

Uploaded PDF file follows on next page.

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs - CI Streed

Key to comments in the right column:
NNN cites citations from ISI Web of Science Cited Reference Search.
IF N.N journal Impact Factor from Clarivate Analytics (Thomson Reuters Journal Citation Reports).

✻[1] **EW Streed**, A Jechow, BG Norton, D Kielpinski **25 cites**
"Absorption imaging of a single atom", *Nature Communications* **3** 933 (2012) **IF 12.1**

First imaging of an atom's shadow. Demonstrated the maximum physical contrast, which bounds imaging performance in damaging UV or x-ray radiation systems. Predicted feasibility of imaging sub-wavelength DNA strand dynamics. Demonstrated using a laser cooled trapped ion and a large numerical aperture microfabricated diffractive lens. Essential step towards the developing the construction of a quantum receiver. Widespread international media coverage including the front page of Nature.com, and featured on Google News, Yahoo! News, CNN.com, Huffington Post, UK Daily Mail, Metro (London), Discover Magazine, National Geographic, Popular Science. Science article by EW Streed in TheConversation.com 26k reads. Subject of a 4 minute Periodic Videos by Professor of Chemistry Sir Martyn Poliakoff with 192k views on YouTube.

[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

✻[2] **EW Streed**, BG Norton, A Jechow, TJ Weinhold, D Kielpinski **52 cites**
"Imaging trapped ions with a microfabricated lens for quantum information processing" **IF 8.5**
Physical Review Letters **106**, 010502 (2011)

First experimental demonstration of a microfabricated lens integrated with an ion trap. Showed that phase Fresnel lenses can have performance suitable for large scale trapped ion quantum computing. Citation rate in Top 10% of published articles for 2011 (ISI Essential Science Indicators, Physics)

[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

✻[3] M Ghadimi, V Blūms, BG Norton, PM Fisher, SC Connell, JM Amini, C Volin, H Hayden, **5 cites**
C-S Pai, D Kielpinski, M Lobino, **EW Streed** **IF 9.1**
"Scalable ion-photon quantum interface based on integrated diffractive mirrors"
Nature Partner Journal Quantum Information **3**, 4 (2017)

First experimental demonstration of a microfabricated ion chip trap with an array of integrated diffractive mirrors. Achieved diffraction-limited, sub-wavelength optical performance with large numerical aperture and coupled ion light into a fibre. Tangible progress towards building small-scale quantum communications routers/repeaters. Citation rate in Top 10% of published articles for 2017 (ISI Essential Science Indicators, Physics)

[ARC FT130100472 2014-2017]

[ARC DP130101613 2014-2016]

✻[4] V Blūms, M Piotrowski, MI Hussain, BG Norton, SC Connell, S Gensemer, M Lobino, **EW Streed** **new!**
"A single-atom 3D sub-attonewton force sensor" *Science Advances* **4** eaao4453 (2018)

First direct measurement of the scattering light force shifting the location of a trapped ion. First to demonstrate 3D super-resolution imaging of a trapped ion with nanometer scale accuracy. Applications to sensing higher-order electric fields of co-trapped particles including biomolecules or nanoparticles. Press coverage in Nature.com Research Highlights and PhysOrg.

[ARC FT130100472 2014-2017]

[ARC DP130101613 2014-2016]

[5] DW Vernooy, VS Ilchenko, H Mabuchi, **EW Streed**, HJ Kimble **317 cites**
"High-Q Measurements of Fused-Silica Microspheres in the Near Infrared" **IF 3.4**
Optics Letters **23** 247-249 (1998)

Record setting monolithic optical resonator. Held world's best reported Quality factor (lowest loss) result for 9 years. Demonstrated fused silica microsphere resonators can have optical performance suitable for cavity QED and photonic processing applications. Technological basis for NASA/JPL spin-off company OEWaves.

[6] D Schneble, Y Torii, M Boyd, **EW Streed**, DE Pritchard, W Ketterle **146 cites**
"The Onset of Matter-Wave Amplification in a Superradiant Bose-Einstein Condensate" **IF 37.2**
Science **300** 475-478 (2003)

First demonstration of Heisenberg uncertainty changing atom-light scattering behavior at short time scales. Discovery of limit to matter wave amplification process by stimulated emission.

✻[7] **EW Streed**, J Mun, M Boyd, GK Campbell, P Medley, W Ketterle, DE Pritchard **97 cites**
"Continuous and Pulsed Quantum Zeno Effect" *Physical Review Letters* **97**, 260402 (2006) **IF 8.5**

200x suppression of a transition is largest Quantum Zeno effect observed to date. Important for quantum computation error suppression schemes and low resource cost preservation of initialisation of quantum memory. First quantitative measurement of continuous Zeno effect.

[8] **EW Streed**, AP Chikkatur, TL Gustavson, M Boyd, Y Torii, D Schneble, GK Campbell, **58 cites**
DE Pritchard, W Ketterle **IF 1.5**
"Large Atom Number Bose-Einstein Condensate Machines"
Review of Scientific Instruments **77** 023106 (2006)

Detailed instructions for building BEC machines. Compared performance limitations between ^{23}Na and ^{87}Rb BECs. Showed three body recombination and trap depth limits practical Rubidium BEC atom number.

✻[9] A Jechow, **EW Streed**, BG Norton, MJ Petrasiunas, D Kielpinski **14 cites**
"Wavelength-scale imaging of trapped ions using a phase Fresnel lens" **IF 3.4**
Optics Letters **36** 1371-1373 (2011)

Highest reported resolution imaging of an isolated atom and largest coherent collection of light from a trapped ion at time of publication. Demonstrated phase Fresnel lenses can deliver near diffraction-limited optical performance and suitable candidates for interfacing photons with ions for quantum networking.

[ARC DP0877936 & Australian Postdoctoral Fellowship 2008-2010]

[10] GK Campbell, AE Leanhardt, J Mun, M Boyd, **EW Streed**, W Ketterle, DE Pritchard **107 cites**
"Photon Recoil Momentum in Dispersive Media" *Physical Review Letters* **94**, 170403 **IF 8.5**
(2005)

Answered the fundamental physics question "What is the momentum of a photon in a dielectric medium?"

D10. Research Opportunity and Performance Evidence (ROPE) - Currently held ARC Projects

(This information is auto-populated from your RMS profile and will include any current Project which has not yet had a Final Report approved and the Project file closed by the ARC. If you have any concerns with the information recorded here, contact your Administering Organisation's Research Office.)

Identifier	Investigators	Admin Organisation	Project Title	Funding	End Date	Final Report Due Date	Final Report Status
DP130101613	Dr Erik Streed ; Prof Joseph Hope ; Dr Andre Carvalho ; Prof David Kielpinski ; Prof Enrique Solano ; Prof Rainer Blatt	Griffith University	Building Schrodinger's cat: large-scale entanglement of trapped ions	$396,000	30/09/2017	30/09/2018	Draft
FT130100472	Dr Erik Streed	Griffith University	Trapped Ion Imaging for Biomolecular Dynamics	$754,820	31/12/2017	31/12/2018	Draft
LP140100797	Prof Joan Vaccaro ; Dr Luke Uribarri ; Prof Stephen Barnett ; Dr Erik Streed	Griffith University	Lightweight battery with more yield than a tonne of coal	$255,409	13/11/2018	13/11/2019	Draft

D11. Eligibility - Role of Partner Investigator

(Please indicate which of the Partner Investigator role options from A6.3.3 of the Funding Rules apply to your role on this Project. Select all options that apply.)

D12. Eligibility - Will you be residing predominantly in Australia for the Project Activity Period?

(This is a 'Yes' or 'No' question. Indicate whether you will be residing predominantly in Australia for the Project Activity Period. If you are applying as a CI and you answer 'No' to this question you will be prompted to contact your Research Office to check your eligibility. If you are a Foreign National, you must reside legally in Australia. Eligibility will be based solely on the information contained in this Proposal.)

Yes

D13. Eligibility - Are you currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date?

(This is a 'Yes' or 'No' question. If you are applying as a CI and your answer is 'Yes' to this question you will be prompted to contact your Research Office. Eligibility will be based solely on the information contained in this Proposal.)

No

D14. Eligibility - Employment Details as at Funding Commencement Date of Project

(This question will be used to determine your eligibility. Your eligibility will be based solely on the information contained in this Proposal. Confirm your employment status at all organisations that you will be associated with as at the Funding Commencement Date. Enter the relevant appointment type and Full-Time Equivalent (FTE) for each organisation.)

Org name	Is this an Eligible Organisation?	Please choose your appointment type for this organisation.	Please enter your FTE for this Organisation
Griffith University	Yes	Employee	1.0

D15. Eligibility - Further Details Regarding Partner Investigator Status - Do you hold a remunerated appointment at an Eligible Organisation?

(At A2 Partner Investigator has been selected as the role type, but it appears that the participant meets the criteria of a Chief Investigator.
NOTE: this question is mandatory ONLY FOR PIs WHO:
• at D12 confirmed that they will reside predominantly in Australia for the Project Activity Period of the proposed Project; AND
• at D13 confirmed that they are not currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date; AND
• at D14 indicated that they would hold either:
- an appointment at an Eligible Organisation equal or greater than 0.2 FTE; OR
- an emeritus appointment at an Eligible Organisation

This is a 'Yes' or 'No' question. If you select 'Yes', you will be further prompted to justify your participation on this Proposal as a PI with reference to sections A6.2 and A6.3 of the Funding Rules.)
Do you hold a remunerated appointment at an Eligible Organisation?

Justification of PI status

D16. Eligibility - Relevant Organisation for this Proposal

(Enter the Organisation that is relevant to your participation on this Proposal, and that you will be associated with as at the Funding Commencement Date. The 'relevant organisation' is the primary organisation that will be supporting your involvement in this Project if it is funded. Note that the Organisation must be listed in D14 for this question to validate.)

Relevant Organisation

Griffith University

D17. What is your time commitment to this Project?

(Enter your time commitment to this Project as a Full-Time Equivalent (FTE). Note that a FTE of 1.0 represents a full-time commitment (i.e. 5 days per week).)

0.5

Part D - Personnel and ROPE (Dr Andre Carvalho)

D1. Personal Details

(To update personal details, click the 'Manage Personal Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Participation Type

Chief Investigator

Title

Dr

First Name

Andre

Second Name

R. R.

Family Name

Carvalho

D4. Qualifications

(To update any qualifications, click on the 'Manage Qualifications' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Conferral Date	AQF Level	Degree/Award Title	Discipline/Field	Awarding Organisation	Country of Award
12/02/2003	Doctoral Degree	Doctor in Sciences (Physics)	Physics	Federal University of Rio de Janeiro	Brazil
08/02/1996	Bachelor Degree	Bachelor in Physics	Physics	PUC-RJ (Catholic University of Rio de Janeiro)	Brazil

D5. Research Opportunity and Performance Evidence (ROPE) - Current and previous appointment(s) / position(s) - during the past 10 years

(To update any details in this table, click on the 'Manage Employment Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile. Refer to the Instructions to Applicants for more information.)

Description	Department	Contract Type	Employment Type	Start Date	End Date	Organisation
Senior Reseach Fellow	Centre for Quantum Dynamics	Contract	Full Time	14/02/2017	14/02/2020	Griffith University
Research Fellow	of Quantum Science	Contract	Full Time	15/12/2005	31/01/2017	The Australian National University

D6. Research Opportunity and Performance Evidence (ROPE) - Academic Interruptions

(You must read the ROPE Statement http://www.arc.gov.au/arc-research-opportunity-and-performance-evidence-rope-statement before filling out this section.)

Have you experienced an interruption that has impacted on your academic record?

Yes

From when

01/11/2002

To when

01/03/2003

FTE of academic interruption

0.3

Details

Between 2002 and 2003 I relocated from Brazil to Germany. In the period of the last 2 months before moving and 2 months after moving I spent, on average, one day and a half per week (0.3FTE) with the organisation of the family relocation (selling house in Brazil, finding accommodation and childcare in Germany, etc.) This affected the research output in 2003.

From when

01/10/2005

To when

01/03/2006

FTE of academic interruption

0.3

Details

Between 2005 and 2006 I relocated from Germany to Australia. In the period of the last 3 months before moving and 3 months after moving I spent, on average, one day and a half per week (0.3FTE) with the organisation of the family relocation. This included job applications and interviews, as well as the logistics of moving houses, finding accommodation, new school for kid, etc. This affected the research output in 2006.

D7. Research Opportunity and Performance Evidence (ROPE) - Details of your academic career and opportunities for research, evidence of research impact and contributions to the field, including those most relevant to this Proposal

(Upload a PDF of no more than five A4 pages with details of your academic career and opportunities, evidence of research impact and contributions to the field.)

Uploaded PDF file follows on next page.

D7. Research Opportunity and Performance Evidence (ROPE) - Career, opportunities and impact - CI Carvalho

AMOUNT OF TIME AS AN ACTIVE RESEARCHER

I was awarded my PhD 15 years ago in February 2003. In that period, I have experienced career disruption twice due to international relocation (2003 and 2005/2006). This would amount a total of 9 months with 0.3 FTE career interruptions.

RESEARCH OPPORTUNITIES

Academic interruptions

My publication output was affected by my international relocations in 2003 and 2006. The time and effort to relocate with the family to a different country affected the research output in those years, as described in Section D6.

Employment situation

Senior Research Fellow, Griffith University, Gold Coast, Australia.	Feb 2017 – present	**1.0 FTE research**
Senior Research Fellow, Centre for Quantum Computation and Communication Technology, Research School of Physics and Engineering, The Australian National University, Canberra, Australia	Dec 2013 – Jan 2017	**0.6 FTE research**
Research Fellow, Centre for Quantum Computation and Communication Technology, Research School of Physics and Engineering, The Australian National University, Canberra, Australia	Jun 2011 – Nov 2013	**0.6 FTE research**
Research fellow, Department of Quantum Science, Research School of Physics and Engineering, The Australian National University, Canberra, Australia	Dec 2005 – May 2011	**1.0 FTE research**
Postdoctoral Fellow, Max-Planck Institute for the Physics of Complex Systems, Dresden, Germany	Jan 2003 – Dec 2005	**1.0 FTE research**

Current and Previous Roles

My current position is at 1.0 FTE research. Since the beginning of 2018, I have been coordinating the Quantum Thermodynamics Research Program under the mentorship of Prof. Joan Vaccaro. The program involves five academic staff, two PhD candidates, and one undergraduate student. I currently supervise one Honours student, one undergraduate research project, and co-supervise two PhD Students. I also continue to supervise two PhD students that started their projects when I was still in my previous position at the ANU.

Despite the nominal 1.0FTE research position, I devote part of my time to other academic activities. Teaching is restricted to supervising undergraduate research projects (3 since 2017). Service activities involve public outreach in events like "Physics in the Pub" (through the Australian Institute of Physics) and "Skype a Scientist" where, so far, I interacted with students from Indonesia and New Zealand. I participate in internal committee work, journal peer review, and also act as assessor for grant applications for both the ARC and international funding agencies (Austria, Germany, and Romania).

In 2007 I was a research fellow at the Department of Quantum Science at the ANU. During this time, I worked in the group led by A/Prof. Joseph Hope within the ARC Centre for Excellence in Quantum-Atom Optics (ACQAO) where I had the opportunity to interact with world-leading experimentalists and theoreticians in atom- lasers and Bose-Einstein condensates. The group supported my effort to lead new research directions and to maintain active collaborations outside Australia.

From June 2011 to January 2017, I worked at the ANU node of the Centre for Quantum Computation and Communication Technology (CQC2T) within the Quantum Networks and Control program led by Prof. Matt James (Engineering). In a combination of complementary skills, Matt in control engineering and myself in quantum optics and open quantum systems, we worked to bring together quantum physics and modern engineering methods to design systems for quantum information applications. In particular, I played a leading role in the collaboration with the quantum memory experimental groups of Prof. P.K. Lam and Dr. Matt Sellars, which led to joint publications with both groups.

During my employment at the ANU, I have also been involved in teaching. I taught third year physics in two occasions (2010, 2012), first year physics for three consecutive years (2013-2015), and have been involved in the restructure of the ANU physics program in 2014 and 2015. I have supervised 17 undergraduate projects and 8 Honours thesis. Including undergraduate student supervision, my effective teaching and service load during this period would correspond to roughly 0.4FTE.

Research mentoring and facilities

At Griffith University, I have access to top-quality research mentoring and research facilities. I am a member of the Centre for Quantum Dynamics that hosts a world-leading theoretical group on quantum optics, quantum information and quantum foundations. The Centre also hosts a number of top laboratories with experiments in ion traps and photon-based quantum information. This provides a vibrant research environment where collaboration between theory and experiments, so crucial to this proposal, is actively promoted and encouraged.

The university and the Centre also provide me with standard academic facilities such as access to research journals, to computer clusters, and travel funding. These are all provided at the appropriate level to perform research planned in this proposal.

Other aspects of career or opportunities for research

In 2014, I was involved in a number of administrative, educational, and outreach activities. I was the treasurer of the ACT Branch of the Australian Institute of Physics, the treasurer for the 2014 AIP Congress in Canberra, and the coordinator of Frame Your Physics (a video competition for school students organised by the AIP). In 2015, I became the Chair of the ACT Branch of the AIP. These activities had an impact on my research output in 2015.

RESEARCH ACHIEVEMENTS AND CONTRIBUTIONS

Invited keynote and speaker addresses (last 10 years) * relevant to this application

* 1 **Invited speaker,**
"Quantum Spin-heat Engine With Trapped Ions", invited seminar presented at the 2017 AIP Summer Meeting, 3-7 December, 2017, Sydney, Australia.

2 **Invited speaker,**
"Tuning quantum measurements to control chaos", invited seminar presented at China-Australia Quantum Control Workshop, 25-28 September, 2016, Hefei, China.

* 3 **Invited Speaker,**
"Ignorance Is Bliss: General and Robust Cancellation of Decoherence via No-Knowledge Quantum Feedback", invited seminar presented at the EMN (Energy, Materials Nanotechnology) Quantum Meeting, 8 to 11 April, 2016, Phuket, Thailand.

✻ 4 **Invited Speaker,**
"Ignorance Is Bliss: General and Robust Cancellation of Decoherence via No-Knowledge Quantum Feedback", invited seminar presented at the 3rd Biennial China-Australia Quantum Control Workshop, 29 September to 3 October, 2014, Brisbane, Australia.

5 **Invited Speaker,**
"Quantum computing with incoherent resources and quantum jumps", invited seminar presented at China-Australia Quantum Control Workshop, 5-8 November, 2012, Beijing, China.

6 **Invited Speaker,**
"Quantum Information Science: what is out there?" Invited seminar presented at NICTA (National Information and Communications Technology Australia), Canberra, 17 June 2010.

7 **Invited Speaker,**
"Robust control of entanglement by quantum-jump-based feedback", invited seminar presented at the XIV Central European Workshop on Quantum Optics, 1-5 June 2007, Palermo, Italy.

Research support income (last 10 years)

National Competitive Grants

✻ **$396,000** ARC Discovery Project DP130101613 "Building Schrodinger's cat: large-scale entanglement of trapped ions", 2013-2017. Role: CI.

Other professional activities

(a) Conference organisation

- Co-chair for the Quantum Stream of the 2017 AIP Summer Meeting, Sydney (2017).
- Member of the International Program Committee of the 11^{th} Workshop on Principles and Applications for Control of Quantum Systems (PRACQSYS), Seattle (2017).
- Member of the organising committee and treasurer for the 21^{st} International Congress of the Australian Institute of Physics, Canberra (2014).

(b) Refereeing, examining and assessing roles

- Journals: Physical Review Letters, Physical Review (A, B, E, and X), Physics Letters A, Journal of Physics A and B, New Journal of Physics, The European Physical Journal D, International Journal of Quantum Information, Europhysics Letters, Physica A, Automatica, Journal of the Optical Society of America B, and Physica Scripta.
- PhD Thesis Examiner, School of Electrical Engineering and Telecommunications, UNSW (2016).
- Assessor of grant proposals: Australian Research Council, Romanian National Research Council, Deutsche Forschungsgemeinschaft (DFG) - German Research Foundation.

(c) Participation in professional societies

- Chair of the ACT Branch of the Australian Institute of Physics (2015-2016).
- Member of the Council for the Australian Institute of Physics (2015-2016).
- Treasurer of the ACT Branch of the Australian Institute of Physics (2012-2015).
- Member of the committee of the ACT Branch of the Australian Institute of Physics (2012-2016).

Describe how your research has led to a significant change or advance of knowledge in your field, and outline how your achievements will contribute to this Proposal.

My research is characterised by the development of theoretical methods in quantum control and quantum information, always keeping a tight connection with experiments and possible applications. This allowed me to establish a number of collaborations with experimental groups and to develop theoretical work for a variety of physical systems including optical cavities, quantum memories, and ion traps, the platform for the heat engine implementation in this proposal. On the theoretical side, the breadth of my research also led to a number of collaborations with different groups around the world on topics like quantum control, quantum thermodynamics, quantum optics, and quantum computing. In the following I will focus on the contributions of relevance to the field of this proposal.

Reservoir Engineering

I developed one of the first proposals of reservoir engineering to screen quantum motional states of trapped ions against decoherence [47] (all citations refer to the numbered publications in section D8). The general idea of designing an effective reservoir dynamics to steer a quantum system towards a desired state was the precursor of much of the work on dissipative state preparation in the field in recent years. I also proposed the use of reservoir engineering for entanglement generation and protection in ion traps [13], applications in microwave cavities [25], as well as the artificial generation of baths at arbitrary temperature [27]. In this proposal, different stages of a memory-powered heat engine involve the interaction of the system with the environment (or reservoir). My experience and achievements in this topic will represent a major contribution to the theoretical goals of this proposal, in particular when it comes to the design of new memory-powered engines for ion traps, as described in Task 2.2 of Section C1.

Entanglement Dynamics and Measures

I proposed one of the earliest genuine entanglement measures for multipartite systems [43,44]. This measure was used for the first quantitative analysis of multipartite entanglement decay under decoherence [44], being a breakthrough in the area at the time and is still a very influential result today. One of the scenarios characterised in these contributions was the dynamics of multipartite entanglement under Mølmer-Sørensen gates in ion traps [43]. This is another example that shows my expertise in modelling trapped ions, the physical system used in our experiments at Griffith University.

Quantum Control

One area that I consistently contributed to in the past ten years is quantum control. I have a vast body of work on the issue of quantum feedback control [14,16,19,24,26,29,31,33,37,38]. These contributions have diverse applications including entanglement protection, decoherence suppression, as well as the control of Bose-Einstein condensates and atom lasers. I have also a number of contributions on the dynamics of monitored quantum systems with applications in various areas, from enhancing entanglement through measurements [13] to a full quantum computing model based on quantum trajectories [21]. Of particular significance is my contribution on quantum-jump-based feedback, which highlighted that measurement design is an important control knob inexistent in classical systems, but of crucial importance in quantum systems.

Another approach to control is the use of pulses that are designed to achieve a desired dynamics in the quantum system. I used this kind of method in a number of contributions in the field of fast gates for trapped ions, most of them as part of an ARC Discovery Project (DP130101613) in collaboration with the Griffith ion trap experimental group [2,6,8,11,13,18,51]. These achievements in quantum control will provide a solid background to this proposal when it comes to engineer and design the dynamics of entropy capacitors, as described in Task 2.3 of Section C1.

Quantum Thermodynamics

Another area of significant contribution to the field and to this proposal are my recent work on quantum

thermodynamics. In [1], for example, I used the methods of reservoir engineering that I developed in [27] to propose an experimental platform to test fluctuation theorems in quantum thermodynamics. In collaboration with CI Vaccaro, and in the context of a previous Linkage Project with Lockheed Martin, I contributed to work that are key foundations for this proposal.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications

i. Publication context and contribution: Upload a PDF of no more than two pages. Provide clear information that explains the contribution and significance of your publications within the context of your discipline/s. This may include the importance/esteem of specific journals in your field; specific indicators of recognition within your field such as first authorship/citations.

Uploaded PDF file follows on next page.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications - CI Carvalho

i. Publication context and contribution

Reference numbers marked [NN] refer to publication NN in **D8 ROPE List of publications** that follows. Citation data are from ISI Web of Science.

Contribution and authorship context

Over the course of my career, I have published papers in a range of different areas, collaborating with a variety of groups, both experimental and theoretical. Therefore, my publications typically feature three to four authors, reflecting the collaborative aspect of my work. To make it easier to assess my contribution, the following pattern applies: I was the main driving force behind the works where I appear as first author, and the one that conceived the ideas and coordinated the work in publications where I am the last author. The remaining publications fall somewhat between these extremes, with occasions where projects were designed in conjunction with collaborators, and others where I was the main supporter of the first author, usually a student or less experienced postdoc.

Significance and impact: citation metrics

In terms of citation and metrics, the quality and impact of my research is evident in the fact that more than 20% of my publications have appeared in high-profile journals, 10 in Physical Review Letters and 1 in Physics Reports, with more than 1200 citations in total. I have an average of more than 25 citations per article (as compared to 11.56 in the discipline of physics), my h-index is 17, and my top 5 cited papers have more than 65 citations each, a number that puts them in the top 10% of physics publications. Two contributions in the area of entanglement measures and dynamics deserve highlight: a Physical Review Letters [44], where I am the leading author, and an invited Physics Report article [43]. They are considered benchmark papers that, together, have received more than 500 citations, lying in the top 1% of physics articles published in those years.

Significance and impact: other measures

Besides the appearance in high profile journals and the number of citations, many of my publications have received media attention and/or have inspired scientific collaborations and projects.

The work on state protection through reservoir engineering in ion traps [47], for example, deserved a comment in the News & Views section of Nature, received more than 80 citations, and inspired an entire section on the book "Exploring the Quantum: Atoms, Cavities, and Photons" by the 2012 Nobel Laureate S. Haroche, and J. M. Raimond. The ideas from this paper are still echoing in a variety of areas.

More recently, a publication in the field of quantum information, quantum optics and control [27] had a strong impact being highlighted by editors of the journal for "its novelty, significance and potential impact on future research". Indeed, three different ideas sprung from this work, with two of them [14,21] being published in Physical Review Letters and featured in various media outlets including the site of the Brazilian Academy of Sciences, the ANU News, and a number of science news blogs and portals. The third one, written in collaboration with colleagues from France and Brazil, was an application of our original idea of engineered reservoirs to the field of quantum thermodynamics, the research area of this LP proposal. My work on quantum feedback in Bose-Einstein condensates from 2013 [16] appeared on the ABC, Fox News, and many others science news websites, lying in the top 5% of all research outputs scored by Altmetric (https://iop.altmetric.com/details/1940205).

Another high-impact publication is the Rapid Communication in Physical Review A on feedback control of entanglement [37]. This paper motivated experimental groups to consider implementing our proposal, laying the foundations for the Discovery Project (DP130101613) in collaboration with the ion traps experimental groups of Prof. Kielpinski at Griffith University and Prof. Rainer Blatt, from Innsbruck. I have six publications resulting from this DP [2,6,8,11,13,18], including one [6] in collaboration with Dr. Erik Streed, the lead CI in the current LP proposal.

It is also important to put in context my previous contributions to the field of this LP proposal. Since my PhD, I used trapped ions as the system of choice for proposing experimental implementations of my theoretical ideas, including the works on reservoir engineering [47], quantum chaos [45, 46], and also on entanglement dynamics [43]. I brought this expertise to the ANU, opening the way to the collaboration that led to the DP mentioned above. Therefore, in most of the ion trap publications, I played a leading role. This is not reflected in the author ordering, which followed seniority rather than individual contributions.

ii. Publication list: Upload a PDF of no more than five pages. List your publications most relevant to this proposal categorised under the following headings: Authored books; Edited books; Book chapters; Referred Journal articles; Fully refereed conference proceedings; Other publication outputs. CVs and theses should not be included in this list. Next to each, provide the Project ID and years funded for any ARC grant on which you were a CI or Fellow from which the item originated.

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D8. Research Opportunity and Performance Evidence (ROPE) - Publications - CI Carvalho

ii. Publication List

Authored books n/a

Edited books n/a

Book chapters n/a

Refereed Journal articles

[1] A. K. Ratcliffe, R. L. Taylor, J. J. Hope, and **A. R. R. Carvalho** **PRL**
"Scaling trapped ion quantum computers using fast gates and microtraps", *Phys. Rev. Lett.* , **120**, 220501 (2018).

[2] J.S.S.T. Wright, T. Gould, **A.R.R. Carvalho**, S. Bedkihal, J. A. Vaccaro,
"Quantum heat engine operating between thermal and spin reservoirs", accepted for publication in *Physical Review A*, **97**, 052104 (2018).

[3] Cyril Elouard, Nadja Kolb Bernardes, **A. R. R. Carvalho**, Marcelo França Santos and Alexia Auffèves,
"Probing quantum fluctuation theorems in engineered reservoirs", *New J. Phys.* **10**, 103011 (2017).

[4] R. L. Taylor, C. D. B. Bentley, J. S. Pedernales, L. Lamata, E. Solano, **A. R. R. Carvalho**, and J. J. Hope,
"A Study on Fast Gates for Large-Scale Quantum Simulation with Trapped Ions", *Scientific Reports* **7**, 46197 (2017). **ARC DP130101613 (2013-2017)**

[5] N. K. Bernardes, **A. R. R. Carvalho**, C. H. Monken, and M. F. Santos,
"Coarse graining a non-Markovian collisional model", *Phys. Rev. A* **95**, 032117 (2017).

[6] J. K. Eastman, J. J. Hope, **A. R. R. Carvalho**,
"Tuning quantum measurements to control chaos", *Scientific Reports* **7**, 44684 (2017).

[7] R. L Lecamwasam, M. R Hush, M. R James, **A. R. R. Carvalho**,
"Measurement-based generation of shaped single photons and coherent state superpositions in optical cavities", *Phys. Rev. A* **95**, 013828 (2017).

[8] M. I. Hussain, M. J. Petrasiunas, C. D B Bentley, R. L. Taylor, **A. R. R. Carvalho**, J. J. Hope, E. W. Streed, M. Lobino, D. Kielpinski,
"Ultrafast, high repetition rate, ultraviolet, fiber laser source: application towards Yb+ fast quantum-logic", *Optics Express* **24**, 16638 (2016).
ARC DP130101613 (2013-2017)

[9] Yi Li, **André R. R. Carvalho**, and Matthew R. James,
"Continuous-mode operation of a noiseless linear amplifier", *Phys. Rev. A* **93**, 052312 (2016).

[10] C. D. B. Bentley, R. L. Taylor, **A. R. R. Carvalho**, and J. J. Hope,
"Stability thresholds and calculation techniques for fast entangling gates on trapped ions", *Phys. Rev. A* **93**, 042342 (2016).
ARC DP130101613 (2013-2017)

[11] S. Fu, **A. R. R. Carvalho**, M. R. Hush, and M. R. James,
"Cross-phase modulation and entanglement in a compound gradient echo memory", *Phys. Rev. A* **93**, 023809 (2016).

[12] G. Guccione, H. Slater, **A. R. R. Carvalho**, B. Buchler, and P. K. Lam,
"Squeezing quadrature rotation in the acoustic band via optomechanics", *Journal of Physics B: Atomic, Molecular and Optical Physics*, **49**, 065401 (2016).

[13] C. D. B. Bentley, **A. R. R. Carvalho**, and J. J. Hope,
"Trapped ion scaling with pulsed fast gates", *New Journal of Physics* **17**, 103025 (2015).
ARC DP130101613 (2013-2017)

[14] N. K. Bernardes, **A. R. R. Carvalho**, C. H. Monken, and M. F. Santos,
"Environmental correlations and Markovian to non-Markovian transitions in collisional models", *Phys. Rev. A* **90**, 032111 (2014).

[15] C. D. Bentley, **A. R. R. Carvalho**, D. Kielpinski, and J. J. Hope, **PRL**
"Detection-Enhanced Steady State Entanglement with Ions", *Phys. Rev. Lett.* **113**, 040501 (2014).
ARC DP130101613 (2013-2017)

[16] S. S. Szigeti, **A. R. R. Carvalho**, J. G. Morley, and M. R. Hush, **PRL**
"Ignorance Is Bliss: General and Robust Cancellation of Decoherence via No-Knowledge Quantum Feedback", *Phys. Rev. Lett.* **113**, 020407 (2014).

[17] R. N. Stevenson, M. R. Hush, **A. R. R. Carvalho**, S. E. Beavan, M. J. Sellars, and J. J. Hope,
"Single photon production by rephased amplified spontaneous emission", *New J. Phys.* **16**, 033042 (2014).

[18] M. R. Hush, S. S. Szigeti, **A. R. R. Carvalho** and J. J. Hope,
"Controlling spontaneous-emission noise in measurement-based feedback cooling of a Bose-Einstein condensate", *New J. Phys.* **15**, 113060 (2013).

[19] M. R. Hush, **A. R. R. Carvalho**, M. Hedges and M. R. James,
"Analysis of the operation of gradient echo memories using a quantum input-output model", *New J. Phys.* **15**, 085020 (2013). Focus issue: Quantum Memory.

[20] C. D. B. Bentley, **A. R. R. Carvalho**, D. Kielpinski, and J. J. Hope,
"Fast gates for ion traps by splitting laser pulses", *New J. Phys.* **15**, 043006 (2013).
ARC DP130101613 (2013-2017)

[21] S. S. Szigeti, S. J. Adlong, M. R. Hush, **A. R. R. Carvalho**, and J. J. Hope,
"Robustness of system-filter separation for the feedback control of a quantum harmonic oscillator undergoing continuous position measurement", *Phys. Rev. A* **87**, 013626 (2013).

[22] **A. R. R. Carvalho**, M. R. Hush and M. R. James,
"Cavity driven by a single photon: conditional dynamics and non-linear phase shift", *Phys. Rev. A* **86**, 023806 (2012).

[23] M. F. Santos, M. Terra Cunha, R. Chaves and **A. R. R. Carvalho**, **PRL**
"Quantum computing with incoherent resources and quantum jumps", *Phys. Rev. Lett.* **108**, 170501 (2012).

[24] M. R. Hush, **A. R. R. Carvalho** and J. J. Hope,
"Number-phase Wigner representation for scalable stochastic simulations of controlled quantum systems", *Phys. Rev. A* **85**, 023607 (2012).

[25] **A. R. R. Carvalho**, A. Kenfack, F. Toscano, J.M. Rost and A. M. Ozorio de Almeida,
"Gaussian representation of extended quantum states", *Phys. Lett. A* **376**, 19 (2011).

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"Distant entanglement protected through artificially increased local temperature", *New J. Phys.* **13**, 013010 (2011).

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"Entanglement in open quantum systems via diffusive quantum trajectories", *Phys. Rev. Lett.* **105**, 210502 (2010).

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"Feedback control of an interacting Bose-Einstein condensate using phase-contrast imaging", *Phys. Rev. A* **82**, 043632 (2010).

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"Number-phase Wigner representation for efficient stochastic simulations", *Phys. Rev. A* **81**, 033852 (2010).

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"Continuous measurement feedback control of a Bose-Einstein condensate using phase-contrast imaging", *Phys. Rev. A* **80**, 013614 (2009).

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"Scalable quantum field simulations of conditioned systems", *Phys. Rev. A* **80**, 013606 (2009).

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"Controlling entanglement by direct quantum feedback", *Phys. Rev. A* **78**, 012334 (2008).

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"Husimi-Wigner representation of chaotic eigenstates", *Proc. R. Soc. A* **464**, 1503 (2008).

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"Stabilizing entanglement by quantum-jump-based feedback", *Phys. Rev. A* **76**, 010301(R) (2007).

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"Effects of measurement back-action in the stabilization of a Bose-Einstein condensate through feedback", *Phys. Rev. A* **76**, 013610 (2007).

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"Entanglement dynamics under decoherence: from qubits to qudits", *Eur. Phys. J. D* **41**, 425-432 (2007).

[44] J. Madroñero, A. Ponomarev, **A. R. R. Carvalho**, S. Wimberger, C. Viviescas, A. Kolovsky, K. Hornberger, P. Schlagheck, A. Krug, and A. Buchleitner,
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"Measures and dynamics of entangled states", *Physics Reports* **415**, 207 (2005).

[46] **André R. R. Carvalho**, Florian Mintert and Andreas Buchleitner, **PRL**
"Decoherence and multipartite entanglement", *Phys. Rev. Lett.* **93**, 230501 (2004).

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"Web-assisted tunneling in the kicked harmonic oscillator", *Phys. Rev. Lett.* ,**93** 204101 (2004).

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"Environmental effects in the quantum-classical transition for the delta-kicked harmonic oscillator", *Phys. Rev. E* **70**, 026211 (2004).

[49] **A. R. R. Carvalho**, P. Milmann, R. L. de Matos Filho and L. Davidovich, **PRL**
"Decoherence, pointer engineering, and quantum state protection"', *Phys. Rev. Lett.* **86**, 4988 (2001).

Fully refereed conference proceedings

[50] **A. R. R. Carvalho** and J. J. Hope,
"Robust control of entanglement by quantum-jump-based feedback" in *Coherence and Quantum Optics IX, Proceedings of the 9th Rochester Conference on Coherence and Quantum Optics*, held at the University of Rochester, USA, June 10-13, 2007, Eds. N. P. Bigelow, J. H. Eberly, and C. R. Stroud, Jr.

[51] **A.R. R. Carvalho**, L. Davidovich, R. L. Matos, and F. Toscano,
"Dissipation, diffusion, and the quantum-classical limit in phase space" in *Proceedings of the 8th International Conference on Squeezed States and Uncertainty Relations*, held at Puebla, Mexico, June 09-13, 2003, Eds. H. Moya Cessa, R. Jauregui, S. Hacyan, and O. Castanos.

Other publication outputs

[52] T. Croucher, J. Wright, **A. R. R. Carvalho**, S.M. Barnett, and J. A. Vaccaro, **Invited**
"Information Erasure", to appear in *Thermodynamics in the quantum regime - Recent Progress and Outlook*, F. Binder, L. Correa, C. Gogolin, J. Anders, G. Adesso Eds., https://arxiv.org/abs/1803.08619.

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs

(Upload a PDF of no more than three A4 pages with a list of your ten career-best academic research outputs related to the Proposal.)

Uploaded PDF file follows on next page.

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs - CI Carvalho

Key to comments in the right column:
NNN cites citations from ISI Web of Science Cited Reference Search.
IF N.N journal Impact Factor from Clarivate Analytics (Thomson Reuters Journal Citation Reports).

[1] **A. R. R. Carvalho**, F. Mintert and A. Buchleitner, "Decoherence and multipartite entanglement", *Phys. Rev. Lett.* 93, 230501, (2004). https://doi.org/10.1016/j.physrep.2005.04.006

228 cites
IF 8.5

This is a breakthrough paper on multipartite entanglement dynamics. Introduced a measure of entanglement that allowed for the first quantitative analysis of entanglement decay in multipartite systems. It lies in the top 1% of physics papers by citation.

[2] F. Mintert, **A. R. R. Carvalho**, M. Kus and A. Buchleitner, "Measures and dynamics of entangled states", *Phys. Rep.* **415**, 207 (2005). https://doi.org/10.1103/PhysRevLett.93.230501

283 cites
IF 17.4

Influential invited review article on the quantitative description of the dynamics of high-dimensional and multipartite entangled systems. Became a benchmark paper in the area of entanglement dynamics under decoherence. This contribution lies in the top 1% of physics papers by citation.

✻[3] **A. R. R. Carvalho** and J.J. Hope, "Stabilizing entanglement by quantum-jump-based feedback", *Phys. Rev. A* **76**, 010301(R) (2007). https://doi.org/10.1103/PhysRevA.76.010301

95 cites
IF 2.9

This paper proposed a robust method to prepare and stabilise entanglement with atoms in cavities using feedback. Influential paper on quantum control as it highlights that quantum measurements introduce an extra control knob, unavailable to classical systems, that can play a crucial role in the design of effective feedback strategies for quantum systems.

✻[4] **A. R. R. Carvalho**, P. Milman, R. L. de Matos Filho and L. Davidovich, "Decoherence, pointer engineering, and quantum state protection", *Phys. Rev. Lett.* **86**, 4988 (2001). https://doi.org/10.1103/PhysRevLett.86.4988

83 cites
IF 8.5

Seminal paper on reservoir engineering to perform quantum state protection with trapped ions. It shows how one can use dissipation to create and protect quantum states. Commented in the News & Views section of Nature. Inspired section 8.3 of the book "Exploring the Quantum: Atoms, Cavities, and Photons" by Nobel laureate S. Haroche and J.M. Raimond.

✻[5] **A. R. R. Carvalho** and Marcelo França Santos, "Distant entanglement protected through artificially increased local temperature", *New J. Phys.* **13**, 013010 (2011). https://doi.org/10.1088/1367-2630/13/1/013010

18 cites
IF 3.8

Presents a proposal to use reservoir engineering and monitoring for entanglement protection. This article introduced ideas that found application in multiple fields such as quantum thermodynamics and quantum feedback control. It led to two other papers in Physical Review Letters (8 and 9 below). It was featured in IOP Select (articles chosen by IOP Editors for their novelty, significance and potential impact on future research).

✻[6] C. D. B. Bentley, **A. R. R. Carvalho**, D. Kielpinski and J. J. Hope, **8 cites**
"Detection-Enhanced Steady State Entanglement with Ions", *Physical Review Letters* **113**, **IF 8.5**
040501 (2014). https://doi.org/10.1103/PhysRevLett.113.040501

Output from DP130101613 - 2013/2017. This article proposed a way to engineer dissipative dynamics to produce entangled states in trapped ions. Prompted interest from experimental groups for being simpler than other methods to generate steady-state entanglement.

[7] **A. R. R. Carvalho**, M. Busse, O. Brodier, C. Viviescas and A. Buchleitner, **28 cites**
"Optimal dynamical characterization of entanglement", *Phys. Rev. Lett.* **98**, 190501 (2007). **IF 8.5**
hhttps://doi.org/10.1103/PhysRevLett.98.190501

Proposed a novel approach to characterise entanglement dynamics under decoherence using quantum jumps. Important result as it substantially simplified the optimisation problem underlying any characterization of entanglement decay.

✻[8] S. S. Szigeti, **A. R. R. Carvalho**, J. G. Morley, and M. R. Hush, **7 cites**
"Ignorance Is Bliss: General and Robust Cancellation of Decoherence via No-Knowledge Quantum Feedback", *Phys. Rev. Lett.* **113**, 020407 (2014). **IF 8.5**
https://doi.org/10.1103/PhysRevLett.113.020407

This paper puts the ideas from [5] in a general framework where engineered and monitored noise can be used to fully cancel decoherence in quantum systems. It was featured in news outlets as an important strategy to achieve the low noise levels required for quantum technological applications

[9] M. F. Santos, M. T. Cunha, R. Chaves, and **A. R. R. Carvalho**, **11 cites**
"Quantum Computing with Incoherent Resources and Quantum Jumps", *Phys. Rev. Lett.* **IF 8.5**
108, 170501 (2012). https://doi.org/10.1103/PhysRevLett.108.170501

This article introduced the idea of using random detections as a resource to quantum computation. Using this innovative approach, all steps on a quantum computation could be achieved by continuous monitoring the system. It was featured in the ANU News, and in a variety of science news websites.

[10] Carlos Viviescas, Ivonne Guevara, **A. R. R. Carvalho**, Marc Busse, Andreas Buchleitner, **23 cites**
"Entanglement dynamics in open two-qubit systems via diffusive quantum trajectories", **IF 8.5**
Phys. Rev. Lett. **105**, 210502 (2010). ht10.1103/PhysRevLett.105.210502

This work proves a conjecture made in [7] by showing that entanglement decay under an amplitude damping channel can be probed directly via quantum trajectories. It also proposes an optical experiment to test it.

D10. Research Opportunity and Performance Evidence (ROPE) - Currently held ARC Projects

(This information is auto-populated from your RMS profile and will include any current Project which has not yet had a Final Report approved and the Project file closed by the ARC. If you have any concerns with the information recorded here, contact your Administering Organisation's Research Office.)

Identifier	Investigators	Admin Organisation	Project Title	Funding	End Date	Final Report Due Date	Final Report Status
DP130101613	Dr Erik Streed ; Prof Joseph Hope ; Dr Andre Carvalho ; Prof David Kielpinski ; Prof Enrique Solano ; Prof Rainer Blatt	Griffith University	Building Schrodinger's cat: large-scale entanglement of trapped ions	$396,000	30/09/2017	30/09/2018	Draft

D11. Eligibility - Role of Partner Investigator

(Please indicate which of the Partner Investigator role options from A6.3.3 of the Funding Rules apply to your role on this Project. Select all options that apply.)

D12. Eligibility - Will you be residing predominantly in Australia for the Project Activity Period?

(This is a 'Yes' or 'No' question. Indicate whether you will be residing predominantly in Australia for the Project Activity Period. If you are applying as a CI and you answer 'No' to this question you will be prompted to contact your Research Office to check your eligibility. If you are a Foreign National, you must reside legally in Australia. Eligibility will be based solely on the information contained in this Proposal.)

Yes

D13. Eligibility - Are you currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date?

(This is a 'Yes' or 'No' question. If you are applying as a CI and your answer is 'Yes' to this question you will be prompted to contact your Research Office. Eligibility will be based solely on the information contained in this Proposal.)

No

D14. Eligibility - Employment Details as at Funding Commencement Date of Project

(This question will be used to determine your eligibility. Your eligibility will be based solely on the information contained in this Proposal. Confirm your employment status at all organisations that you will be associated with as at the Funding Commencement Date. Enter the relevant appointment type and Full-Time Equivalent (FTE) for each organisation.)

Org name	Is this an Eligible Organisation?	Please choose your appointment type for this organisation.	Please enter your FTE for this Organisation
Griffith University	Yes	Employee	1

D15. Eligibility - Further Details Regarding Partner Investigator Status - Do you hold a remunerated appointment at an Eligible Organisation?

(At A2 Partner Investigator has been selected as the role type, but it appears that the participant meets the criteria of a Chief Investigator.
NOTE: this question is mandatory ONLY FOR PIs WHO:
• at D12 confirmed that they will reside predominantly in Australia for the Project Activity Period of the proposed Project; AND
• at D13 confirmed that they are not currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date; AND
• at D14 indicated that they would hold either:
- an appointment at an Eligible Organisation equal or greater than 0.2 FTE; OR
- an emeritus appointment at an Eligible Organisation

This is a 'Yes' or 'No' question. If you select 'Yes', you will be further prompted to justify your participation on this Proposal as a PI with reference to sections A6.2 and A6.3 of the Funding Rules.)
Do you hold a remunerated appointment at an Eligible Organisation?

Justification of PI status

D16. Eligibility - Relevant Organisation for this Proposal

(Enter the Organisation that is relevant to your participation on this Proposal, and that you will be associated with as at the Funding Commencement Date. The 'relevant organisation' is the primary organisation that will be supporting your involvement in this Project if it is funded. Note that the Organisation must be listed in D14 for this question to validate.)

Relevant Organisation

Griffith University

D17. What is your time commitment to this Project?

(Enter your time commitment to this Project as a Full-Time Equivalent (FTE). Note that a FTE of 1.0 represents a full-time commitment (i.e. 5 days per week).)

0.4

Part D - Personnel and ROPE (Prof Joan Vaccaro)

D1. Personal Details

(To update personal details, click the 'Manage Personal Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Participation Type

Chief Investigator

Title

Prof

First Name

Joan

Second Name

Alfina

Family Name

Vaccaro

D4. Qualifications

(To update any qualifications, click on the 'Manage Qualifications' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Conferral Date	AQF Level	Degree/Award Title	Discipline/Field	Awarding Organisation	Country of Award
03/12/1990	Doctoral Degree	PhD	Theoretical physics	Griffith University	Australia
13/04/1985	Bachelor Honours Degree,Graduate Certificate, Graduate Diploma	BSc Honours 1st Class	Theoretical physics	Griffith University	Australia
07/04/1984	Bachelor Degree	BSc	Experimental physics, physical mathematics and electronics and scientific instrumentation	Griffith University	Australia

D5. Research Opportunity and Performance Evidence (ROPE) - Current and previous appointment(s) / position(s) - during the past 10 years

(To update any details in this table, click on the 'Manage Employment Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile. Refer to the Instructions to Applicants for more information.)

Description	Department	Contract Type	Employment Type	Start Date	End Date	Organisation
Professor	School of Natural Sciences	Permanent	Full Time	01/01/2018		Griffith University
Associate Professor	School of Biomolecular and Physical Sciences	Permanent	Full Time	01/01/2011	31/12/2017	Griffith University

Senior Lecturer	School of Science	Permanent	Full Time	01/08/2005	31/12/2010	Griffith University

D6. Research Opportunity and Performance Evidence (ROPE) - Academic Interruptions

(You must read the ROPE Statement http://www.arc.gov.au/arc-research-opportunity-and-performance-evidence-rope-statement before filling out this section.)
Have you experienced an interruption that has impacted on your academic record?

Yes

From when

01/01/2004

To when

01/01/2008

FTE of academic interruption

0.3

Details

I experienced a period of depression associated with increasing gender dysphoria from early 2004 until my transition from male to female in January 2007. There were also major changes in my personal and working life as I began living as a female from 2007. My capacity to perform high-quality research was severely affected during this period.

D7. Research Opportunity and Performance Evidence (ROPE) - Details of your academic career and opportunities for research, evidence of research impact and contributions to the field, including those most relevant to this Proposal

(Upload a PDF of no more than five A4 pages with details of your academic career and opportunities, evidence of research impact and contributions to the field.)

Uploaded PDF file follows on next page.

D7. Research Opportunity and Performance Evidence (ROPE) - Career, opportunities and impact - CI Vaccaro

AMOUNT OF TIME AS AN ACTIVE RESEARCHER

I was awarded my PhD 27 years ago in December 1990, and in that period I experienced a total of 4 years (at 0.3 FTE) of academic interruptions as described below.

RESEARCH OPPORTUNITIES

Academic interruptions

I experienced a period of depression associated with increasing gender dysphoria from early 2004 until my transition from male to female in January 2007. There were also major changes in my personal and working life as I began living as a female from 2007. My capacity to perform high quality-research was severely affected during this period.

Employment situation

Lecturer in Information Systems (computing), Griffith University, Brisbane, Australia. My opportunity for physics research was limited in this position.	Sep 1989 – Mar 1994	**0.4 FTE research**
Postdoctoral research fellow, Max-Planck-Gesellschaft, Workgroup on "Nonclassical Light", Berlin, Germany	Apr 1994 – Mar 1995	**1.0 FTE research**
Postdoctoral research fellow, Physics Department, The Open University, Milton Keynes, UK	Apr 1995 – Aug 1997	**1.0 FTE research**
Senior Lecturer, Department of Physical Sciences, University of Hertfordshire, Hatfield, UK	Sep 1997 – Dec 1999	**0.4 FTE research**
Reader in Physics, Department of Physics, Astronomy and Mathematics, University of Hertfordshire, Hatfield, UK	Jan 2000 – Aug 2005	**0.4 FTE research**
Senior Lecturer, School of Science, Griffith University, Brisbane, Australia	Sep 2005 – Dec 2010	**0.4 FTE research**
Associate Professor, School of Biomolecular and Physical Sciences, Griffith University, Brisbane, Australia	Jan 2011 – Dec 2017	**0.4 FTE research**
Professor, School of Natural Sciences, Griffith University, Brisbane, Australia	Jan 2018 – present	**0.4 FTE research**

Current Roles

My position has a standard academic profile of 0.4 FTE research, 0.4 FTE teaching and 0.2 FTE service. However, Linkage Project LP140100797 provides me with funds for a teaching buyout (0.4 FTE for 3 years from November 2014). I have also undertaken substantial commercial consultative research (0.4 FTE) for Lockheed Martin Corporation from July 2013 at the average rate of $118k per year. The combination of the consultative funds and the LP teaching buyout have allowed me to continuously hire 1.0 FTE lecturer level B/C to replace my position from July 2013 to June 2018.

In my 0.4 EFT research and 0.4 EFT commercial consulting roles I oversee the Quantum Thermodynamics Research Program which is a collaboration of 4 faculty staff, a senior research fellow and 2 PhD students. I supervise and mentor 2 junior staff members and co-supervise the 2 PhD students.

My 0.2 EFT service fraction involve internal committee work, public outreach and academic service as peer reviewer etc.

Research mentoring and facilities

Griffith University offers research mentoring by a senior research academic as part of its Academic Staff Career Development Procedures document number 2017/0000505. When the need arises, I consult Emeritus Prof. David Pegg FAA and Prof. Howard Wiseman FAA, both at Griffith University, for advice concerning research and former Head of School Prof Tim Ryley, Pro Vice Chancellor Prof. Andrew Smith and Senior Deputy Vice Chancellor (Research) Prof. Ned Pankhurst for advice on funding, career progression etc.

The research facilities available to me in the Centre for Quantum Dynamics are the standard academic environment with institutional access to research journals, computing facilities, and funding of approximately $10k per year are more than adequate to carry out the theory-based research planned in this proposal.

RESEARCH ACHIEVEMENTS AND CONTRIBUTIONS

Invited keynote and speaker addresses (last 10 years) * relevant to this application

* 1 **Invited speaker,**
"The cost of information erasure in atomic and spin systems",
The 8th Asian International Seminar on Atomic and Molecular Physics (AISAMP8), University of Western Australia, Perth, Australia, November 24-28, 2008.

* 2 **Invited Speaker,**
"Erasure of information under conservation laws",
Quantum Information and Foundations of Thermodynamics, ETH Zurich, Switzerland, 9-12 August 2011.

* 3 **Invited Speaker,**
"Erasing Information and the Thermodynamical Paradigm at the Nanoscale",
World Congress on Nano Science & Technologies 2012, Qingdao, China, 26-28 October 2012.

* 4 **Invited Speaker,**
"Single reservoir heat engine: controlling the spin",
Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT13), Prague, Czech Republic, 29 July - 3 August 2013.

5 **Invited Speaker,**
"Quantum mechanism that makes time different to space",
Frontiers of Quantum and Mesoscopic Thermodynamics, Prague, Czech Republic, 27 July-1 August, 2015.

6 **Invited Speaker,**
"Making sense of a time symmetric universe: time travelling in both directions",
The Time Machine Factory: [Unspeakable, Speakable] on Time Travel, Turin, Italy, 25-28 October 2015.

7 **Invited Speaker,**
"Quantum asymmetry between time and space & the origin of dynamics",
International School and Conference on Quantum Information, Institute of Physics, Bhubaneswar, India 9-18 February 2016.

* 8 **Invited Speaker,**
"Sharing quantum coherence (and other asymmetries)",
Fifth Quantum Thermodynamics Conference (QTD5), Oxford, UK, 13-17 March 2017.

9 **Invited Speaker,**

"Physical signatures of the quantum nature of time",
Frontiers of Quantum and Mesoscopic Thermodynamics FQMT17, Prague, Czech Republic, 9-15 July 2017.

10 **Plenary speaker & Discussion Panellist,**
"Quantum theory of time",
Women in Physics Canada WIPC Conference, Institute for Quantum Computing, University of Waterloo, Canada, 26-28 July 2017.

11 **Invited Speaker,**
"The quantum nature of time and the origin of dynamics",
Foundations of quantum mechanics and their impact on contemporary society, The Royal Society, London, UK, 11-12 December 2017.

Research support income (last 10 years)

Internal

$9,859, Griffith University Research Project "Quantum Physics and Information" Jan 2009 − Dec 2010.

Commercial research contracts

$171,707, Lockheed Martin Corporation, "Information Erasure and Coherence in Quantum Dots", Aug 2013-Jul 2014.

$96,470, Lockheed Martin Corporation, "Information Erasure and Coherence in Quantum Dots (Coherence Capacitor)", Aug 2014-Jul 2015.

$263,120 Lockheed Martin Corporation, "Information Erasure and Coherence in Quantum Dots (Coherence Capacitor) Year 3 2016", Nov 2016-Oct 2017.

National Competitive Grant (I am the sole Chief Investigator)

$749,409 ARC Linkage Project LP140100797 "Lightweight battery with more yield than a tonne of coal", Jan 2014-Dec 2017.

Describe how your research has led to a significant change or advance of knowledge in your field, and outline how your achievements will contribute to this Proposal.

Nonclassical properties of light

I was the first to recognise that the amplification of squeezed light with linear optical amplifiers could be improved using phase sensitive (squeezed) amplifiers (refereed papers [3]-[5]). I was also first to investigate the phase properties of nonclassical states of light [6,10], non-linear materials (Kerr media) [23] and linear amplifiers [14,15] in terms of the Pegg-Barnett phase formalism.

Quantum phase operator

I have examined more fundamental questions concerning the definition of quantum optical phase including the consistency of various phase formalisms [12] and the treatment of the Pegg-Barnett formalism in the infinite dimensional limit [16,21,22]. This work helped resolve some confusion in the literature.I developed the minimum uncertainty states and the so-called intelligent states associated with the photon number and phase operators [7]. This had never been done before, and the work remains a cornerstone for the theory of quantum phase. I introduced a new phase formalism based on a Hilbert space which includes vectors representing states of infinite photon number [18]. This work led to the definition of a new Wigner function for the photon number and phase observables [20,27]. The new Wigner function is unique in the sense that it is the only quasiprobability distribution introduced to date for which the marginal distributions are the photon number and the phase probability distributions. It gives new insights into the number-phase properties of non-classical states. My work on the theory of the quantum phase operator from its beginning in 1989 lead to my **co-authoring the book** [1] in 2007 that reviews the research field.

Electromagnetically induced transparency (EIT) in cold atomic gases

I developed a technique for probing the long-range spatial order in 1 dimensional optical lattices [29] in laser cooled gasses (which was previously thought impossible). I gave the theoretical support to a collaboration which investigated electromagnetically induced transparency (EIT) experimentally. Our collaboration was the first to demonstrate EIT in laser cooled gases, transient EIT and EIT with weak fields [33,34]. We also demonstrated EIT and optical gain in novel transition configurations [42,43,48,49]. I developed a three-dimensional model of EIT and related effects using stochastic wavefunctions [30]. This model gives a clear pictorial representation of the underlying physics of "counter-intuitive pulse sequences" in population transfer and EIT.

Robust states of open quantum systems

I showed how the phase of a Bose-Einstein condensate could be interpreted in terms of robust states [28] and that these states play an important role in the emergence of preferred states in open quantum systems [44]. I applied robust states analysis to the state of an atom laser showing the effect of the nonlinearities in the atomic cloud [37,46,47].

Quantum remote control

I have proven the no-go theorem for quantum remote control, showing it is not possible to arbitrarily control a quantum system remotely [40]. This theorem is on par with the no-cloning theorem of Wootters and Zurek. I then showed a restricted class of operation could be implemented remotely [45]. The latter work has been confirmed experimentally by Xiang et al. *Phys. Rev. A* 71, 044304 (2005).

Experimental demonstration of quantum coding

I designed a linear-optical experiment to demonstrate the principle of quantum coding (quantum data compression). This principle lies at the foundation of quantum information and underpins the concept of the qubit as a unit of quantum information. The experiment was performed by Sasaki's group at the Communications Research Laboratory (CRL), Tokyo [51,52].We have been granted patents in the UK, Japan and the USA covering the techniques involved. I am a named inventor on the following **patents**:

GB 2400252 A, "Optical apparatus for implementing Schumacher's quantum data compression", 6 April 2005

Japan 3858067, "Quantum source coding apparatus and quantum information communication system", 29 September 2006.

US 07403713 B2, "Quantum source coding apparatus and quantum information communication system", 22 July 2008.

Superselection rules, asymmetry and reference systems, and resource theory

My work on entanglement in the presence of superselection rules and the quantification of the associated reference systems (also called reference frames) is central to understanding entanglement and other nonlocal resources [50,53,54,56,57,71]. Superselection rules arise from conservation laws or other symmetries and limit the physical operations possible, and thus they limit the states that are physically accessible. They arise in a fundamental context, e.g. from the conservation of lepton number, or operationally, e.g. the invariance to global phase shifts. I was concerned with the latter within the framework of quantum information theory. I was **invited to give a talk** on this topic at the international workshop on *Non-locality of Quantum Mechanics and Statistical Inference*, Kyoto Sangyo University, Kyoto, 8-9 September, 2003. Later work [53,54,57] examined the ability of a system to act as a reference to break the superselection rule (and associated symmetry). This research led to the definition of the **asymmetry** measure $A_G(\hat{\rho})$ of a system in state $\hat{\rho}$ with respect to symmetry group G and the introduction of **resource theory of reference systems** [56], both of which are now key concepts in quantum information theory.

Particle-wave duality and Complementarity

One of the basic elements of quantum theory that sets it apart from classical theory is the complementarity

principle which restricts the information about particular observables of a quantum system. I have found that this principle can be framed in terms of the dichotomy between the symmetry and asymmetry of a system with respect to a given symmetry group [60].

Quantum voting and data security

I introduced the first quantum protocol for voting [55] based on the use of a distributed entangled state to ensure that the votes are anonymous. The protocol represents a N-fold reduction in computational complexity, where N is the number of voters.

Erasure of information

I challenged the accepted wisdom that the erasure of information incurs an energy cost according to Landauer's erasure principle. I have shown that by replacing the conventional thermal reservoir with a spin reservoir the cost of erasure can, in principle, be in terms of spin angular momentum and not energy [70,58,62,65]. The significance of this result for the foundations of Thermodynamics cannot be overstated. By resolving Maxwell's demon paradox, Landauer's erasure restores the validity Second Law; as such, it is regarded as being equivalent to the Second Law. The new erasure mechanism implies a new statement of the Second Law is needed. Indeed, erasing the memory of the demon using a spin reservoir means all the heat in a thermal reservoir can be extracted in the form of mechanical work, in contradistinction to historical statements of the Second Law. This work led to a research program developing theory in partnership with Lockheed Martin Corporation that has resulted in commercial research contracts totalling over **$500k** and a ARC Linkage Project LP140100797 "Lightweight battery with more yield than a tonne of coal" 2014-2018 of **$750k** and resulted publications [65,74,66]. The current proposal LP180100096 "A Memory Powered Engine" represents a largely experimental research program that would implement and test the theory and heat engine designs developed under LP140100797.

Quantum nature of time – overturning the current paradigm in physics

Over the last 10 years I have devoted about half of my research to exploring the connection between the violation of time reversal invariance (T violation) and the physical nature of time [2,59,63,64,75]. The basis of this work is the following. Time has been recognised as being asymmetric in direction for millennia. This asymmetry was first given a formal foundation 150 years ago in the second law of thermodynamics in terms of entropy increasing over time. Ninety years ago, Eddington introduced the concept of an "arrow of time" that points in the direction of the increase in entropy, and thus into the future. Many other arrow of time have since been identified; e.g. one is the cosmological arrow that points away from a small hot, dense universe. All such arrows, however, can be explained as arising from a system undergoing time symmetric dynamics subjected to **time asymmetric boundary conditions**. For example, thermodynamics can be derived from statistical mechanics which is based on time symmetric dynamical laws such as Newton's laws etc. where the increasing entropy result is a direct consequence of setting low initial entropy and high final entropy as boundary conditions. Similarly, the cosmological arrow is based on time symmetric general relativity in combination with a small initial and large final universe as the boundary conditions. While understanding the consequences of the asymmetrical boundary conditions are clearly important, they do not reveal anything about the nature of dynamics itself, which is simply assumed to exist. T violation, however, is a consequence of the weak interaction and represents an **time asymmetric dynamical law**. As such, it is the only thing that could give us insight into the nature of dynamics, and thus time, itself. I am the only person exploring this connection.

My approach has been to construct a quantum formalism based on sums over paths of the kind Feynman introduced, where the absence of T violation results in a universe which is static (i.e. it is devoid of time evolution and conservation laws), but where time evolution and conservation laws arise when T violation processes are included. The result is a theory that attributes the **origin of dynamics** to T violation. It is a quantum theory of time. Work is currently underway formalising experimentally testable predictions of the theory. If verified, this work would represent a major shift in our understanding of time of a kind not seen for a century.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications

i. Publication context and contribution: Upload a PDF of no more than two pages. Provide clear information that explains the contribution and significance of your publications within the context of your discipline/s. This may include the importance/esteem of specific journals in your field; specific indicators of recognition within your field such as first authorship/citations.

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D8. Research Opportunity and Performance Evidence (ROPE) - Publications - CI Vaccaro

i. Publication context and contribution

References marked [NN] refer to publication NN in **D8 ROPE List of publications** that follows.
Citation data are from ISI Web of Science.

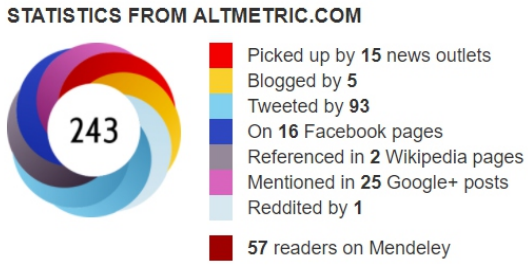
Citation Metrics

I have a total of 77 publications, with a number of them in the the prestigious Physical Review Letters and in the Proceedings of the Royal Society. I have a h-index of 23, more than 1600 citations in total, and over 22 citations per article on average (as compared with the average of 11.26 for the physics discipline). These citations are a testament of the impact of my contributions to the fields of quantum optics, quantum information, quantum thermodynamics and quantum foundations, as described in Section D7.

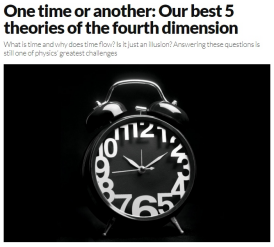
Some individual contributions deserve highlight due to their innovative character and impact. On the issue of the phase properties of nonclassical light, paper [6] received **95 citations**, for example. My work on quantum phase operator resolved some confusion in the literature and the publications [12,16] have attracted a total of **98 citations**. In [7], I developed the minimum uncertainty states and the so-called intelligent states associated with the photon number and phase operators. This had never been done before, and the work remains a cornerstone for the theory of quantum phase and is highly cited **(56 citations)**. My works [20,27] on the Wigner function for the photon number and phase received, together, a total of **94 citations**. In the context of Electromagnetic Induced Transparency, my contributions [33,34,42,43,48] have attracted an average of over **30 citations per publication**, which is indicative of its importance. My papers on quantum remote control [40,40] have received together **225 citations** in total, while my work on entanglement in the presence of superselection rules [50] was published in **Physical Review Letters** journal and has attracted **over 160 citations**.

Of particular importance for this project is my work on erasure of information. The first paper on this topic [58] is published in the **Proceedings of the Royal Society A**, the second [62] was an **invited contribution**, and the third [65] is published in **Physical Review Letters**. As mentioned in Section D7, more than citations, this work led to a whole research program developing theory in partnership with Lockheed Martin Corporation and supported by the ARC.

Besides the highly cited publications in high profile journals, many of my papers have attracted the interest of the media and the public in general. My contribution on T violation and the theory of time is an example of that. This paper and has had an exceptionally positive reception. The statistics accumulated by Altmetric are shown in Fig. 1(a). The publishers website[1] also reports that the paper has been accessed online over 50,000 times and has been downloaded in pdf form over 9,000 times.



(a)



(b)

Figure 1: (a) Almetric statistics for my paper "Quantum asymmetry between time and space" available online at http://rspa.royalsocietypublishing.org/content/472/2185/20150670.article-info
(b) Image taken from New Scientist article "One time or another: Our best 5 theories of the fourth dimension" by Anil Ananthaswamy which includes my quantum theory of time and is available online at https://www.newscientist.com/article/2120135-one-time-or-another-our-best-5-theories-of-the-fourth-dimension/

[1] http://rspa.royalsocietypublishing.org/content/472/2185/20150670.article-info

Evidence of its acceptance by physicists is clear from requests by program committees for me to give 6 invited talks on the theory at international physics conferences (listed as talks **5,6,7,9,10** and **11** in the section **Invited keynote and speaker addresses** in **D7 ROPE Career, opportunities and impact**). I was also invited to contribute a chapter (Output [2] in the list) alongside leading thinkers of our time (including **Nobel Laureate 't Hooft** and **Noam Chomsky**) in the book "Space, Time and the Limits of Human Understanding" co-edited by eminent physicist G. Ghirardi. The invitation to contribute to this book essentially sanctions my theory for a broad audience.

My theory is also described as **one of the 5 best theories on time** by *New Scientist* magazine, 4 Feb 2017 as shown in Fig. 1(b). My revolutionary theory has clearly drawn positive international attention.

ii. Publication list: Upload a PDF of no more than five pages. List your publications most relevant to this proposal categorised under the following headings: Authored books; Edited books; Book chapters; Referred Journal articles; Fully refereed conference proceedings; Other publication outputs. CVs and theses should not be included in this list. Next to each, provide the Project ID and years funded for any ARC grant on which you were a CI or Fellow from which the item originated.

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D8. Research Opportunity and Performance Evidence (ROPE) - Publications - CI Vaccaro

ii. Publication list

Authored books n/a

Edited books

[1] S.M. Barnett and J.A. Vaccaro, Editors,
"The Quantum Phase Operator: A Review" (Taylor and Francis, London, 2007) ISBN 9781584887607.

Book chapters

[2] J. A. Vaccaro, **Invited**
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Space, Time and the Limits of Human Understanding, S. Wuppuluri, G. Ghirardi Eds., (Springer International, Cham, Switzerland, 2016) p. 185–201, Ch. 15 http://dx.doi.org/10.1007/978-3-319-44418-5_15

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D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs

(Upload a PDF of no more than three A4 pages with a list of your ten career-best academic research outputs related to the Proposal.)

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D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs - CI Vaccaro

Key to comments in the right column:
NNN cites citations from ISI Web of Science Cited Reference Search.
IF N.N journal Impact Factor from Clarivate Analytics (Thomson Reuters Journal Citation Reports).

[1] H.M. Wiseman and **J.A. Vaccaro**, "Entanglement of indistinguishable particles shared between two parties", *Physical Review Letters* **91**, 097902 (2003). http://dx.doi.org/10.1103/PhysRevLett.91.097902

166 cites
IF 8.5

This is one of the first papers to quantify the quantum entanglement carried by indistinguishable particles. It shows that the indistinguishability is represented by superselection rules that act on the Hilbert space to limit the entanglement. Superselection rules and their associated references are central to understanding the quantum entanglement and nonlocal reference resource needed to support it. The specific superselection rule studied in the paper is a U(1) symmetry. This fact led us to quantify the reference resource for arbitrary symmetry groups in paper [6] below.

[2] S.F. Huelga, **J.A. Vaccaro**, A. Chefles and M.B. Plenio, "Quantum Remote Control - Teleportation of Unitary Operations", *Physical Review A*, **63** 042303 (2001). http://dx.doi.org/10.1103/PhysRevA.63.042303

138 cites
IF 2.9

Proves that it is not possible to arbitrarily control a quantum system remotely. This theorem is on par with the celebrated no cloning theorem of Wootters and Zurek. It has been demonstrated by experiment.

[3] **J.A. Vaccaro** and D.T. Pegg, "Phase properties of squeezed states of light", *Optics Communications* **70**, 529-534 (1989). https://doi.org/10.1016/0030-4018(89)90377-5

95 cites
IF 1.6

This paper establishes, for the first time, the canonical phase properties of squeezed states of light. It makes use of the Pegg-Barnett phase formalism introduced in the previous year.

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57 cites
IF 2.9

I introduce here a new Wigner function whose marginal distributions are the photon number and phase probability distributions. It gives new insights into the number-phase properties of light.

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50 cites
IF 2.9

Introduces the first quantum protocol for secure voting. The protocol represents a N-fold reduction in computational complexity compared to classical schemes, where N is the number of voters.

✻[6] **J.A. Vaccaro**, F. Anselmi, H M. Wiseman and K. Jacobs, **39 cites**
"Tradeoff between extractable mechanical work, accessible entanglement, and ability to act as a reference system, under arbitrary superselection rules", *Physical Review A* 77, 032114 (2008) http://dx.doi.org/10.1103/PhysRevA.77.032114 **IF 2.9**

This work studies superselection rules associated with arbitrary symmetry groups G. It introduces the entropic measure A_G, called ***asymmetry***, of the ability of one system to act as a quantum reference for another system. It also establishes **quantum resource theory** for quantum reference systems (sometimes called "quantum reference frames"). Both asymmetry and the reference resource theory are major themes in quantum physics today.

[7] Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, **13 cites**
"Experimental demonstration of quantum source coding", *Physical Review Letters* **91**, 217902 (2003). http://dx.doi.org/10.1103/PhysRevLett.91.217902 **IF 8.5**

Experimental demonstration of the principle of quantum coding. This principle lies at the foundation of quantum information and underpins the concept of the qubit as a unit of quantum information.

✻[8] **J.A. Vaccaro** and S.M. Barnett, **13 cites**
"Information erasure without an energy cost", *Proceedings of the Royal Society A* **467**, 1770-1778 (2011). http://dx.doi.org/10.1098/rspa.2010.0577 **IF 2.1**

Overturns the accepted view that the erasure of information incurs an energy cost (Landauer's principle) and demonstrates the utility of thermodynamics operations constrained by multiple conserved quantities. It is a cornerstone publication for at foundations of quantum thermodynamics.

[9] **J.A. Vaccaro**, **9 cites**
"Particle-wave duality: a dichotomy between symmetry and asymmetry", *Proceedings of the Royal Society A*, **468**, 1065-1084 (2012). http://dx.doi.org/10.1098/rspa.2011.0271 **IF 2.1**

Gives fresh insight into the particle-wave duality by recasting it as a compromise between the symmetry and asymmetry of an arbitrary quantum system with respect to a symmetry group.

[10] **J.A. Vaccaro**, **1 cite**
"Quantum asymmetry between time and space", *Proceedings of the Royal Society A*, **472**, 2185 (2016). http://dx.doi.org/10.1098/rspa.2015.0670 **IF 2.1**

This paper addresses the physical nature of Time. Until relatively recently, all fundamental physical laws were thought to be unchanged by a reversal of the direction of time, a property called time reversal symmetry. However, the last two decades have confirmed that the time evolution of certain subatomic particles, K and B mesons, would be different if the direction of time evolution was reversed. This situation represents a violation of time reversal symmetry (T violation). As K and B mesons are part of the universe, the universe as a whole necessarily exhibits T violation as well. Because of this there are **two versions of the Hamiltonian**, one for each direction of time evolution.

All conventional physical theories accommodate only a single version of the Hamiltonian and the time evolution it describes (into the future, by default). This endows the prevailing paradigm with a deeply rooted time asymmetry in the choice of the direction of time evolution and its concomitant version of the Hamiltonian. However, the universe must be

time symmetric at a fundamental level. The failure of the prevailing paradigm to providea fundamental time-symmetric description that accommodates time evolution in both directions of time and both Hamiltonians represents the **T violation anomaly**. This subtle anomaly calls a paradigm shift and the development of new theory—the paper above introduces that theory.

Previously time evolution was thought to be an elemental property of the universe; in other words, the occurrence of time evolution was thought to be unquestionable. However, in my new theory, a universe that does not exhibit T violation is found to have no time evolution (i.e. it is "static") and, conversely, one that does exhibit T violation is found to undergo unbounded time evolution. This means that the new theory gives a mathematical framework in which T violation is the **origin of dynamics** in the universe. This is a revolutionary concept.

D10. Research Opportunity and Performance Evidence (ROPE) - Currently held ARC Projects

(This information is auto-populated from your RMS profile and will include any current Project which has not yet had a Final Report approved and the Project file closed by the ARC. If you have any concerns with the information recorded here, contact your Administering Organisation's Research Office.)

Identifier	Investigators	Admin Organisation	Project Title	Funding	End Date	Final Report Due Date	Final Report Status
LP140100797	Prof Joan Vaccaro ; Dr Luke Uribarri ; Prof Stephen Barnett ; Dr Erik Streed	Griffith University	Lightweight battery with more yield than a tonne of coal	$255,409	13/11/2018	13/11/2019	Draft

D11. Eligibility - Role of Partner Investigator

(Please indicate which of the Partner Investigator role options from A6.3.3 of the Funding Rules apply to your role on this Project. Select all options that apply.)

D12. Eligibility - Will you be residing predominantly in Australia for the Project Activity Period?

(This is a 'Yes' or 'No' question. Indicate whether you will be residing predominantly in Australia for the Project Activity Period. If you are applying as a CI and you answer 'No' to this question you will be prompted to contact your Research Office to check your eligibility. If you are a Foreign National, you must reside legally in Australia. Eligibility will be based solely on the information contained in this Proposal.)

Yes

D13. Eligibility - Are you currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date?

(This is a 'Yes' or 'No' question. If you are applying as a CI and your answer is 'Yes' to this question you will be prompted to contact your Research Office. Eligibility will be based solely on the information contained in this Proposal.)

No

D14. Eligibility - Employment Details as at Funding Commencement Date of Project

(This question will be used to determine your eligibility. Your eligibility will be based solely on the information contained in this Proposal. Confirm your employment status at all organisations that you will be associated with as at the Funding Commencement Date. Enter the relevant appointment type and Full-Time Equivalent (FTE) for each organisation.)

Org name	Is this an Eligible Organisation?	Please choose your appointment type for this organisation.	Please enter your FTE for this Organisation
Griffith University	Yes	Employee	1

D15. Eligibility - Further Details Regarding Partner Investigator Status - Do you hold a remunerated appointment at an Eligible Organisation?

(At A2 Partner Investigator has been selected as the role type, but it appears that the participant meets the criteria of a Chief Investigator.
NOTE: this question is mandatory ONLY FOR PIs WHO:

• at D12 confirmed that they will reside predominantly in Australia for the Project Activity Period of the proposed Project; AND
• at D13 confirmed that they are not currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date; AND
• at D14 indicated that they would hold either:
- an appointment at an Eligible Organisation equal or greater than 0.2 FTE; OR
- an emeritus appointment at an Eligible Organisation

This is a 'Yes' or 'No' question. If you select 'Yes', you will be further prompted to justify your participation on this Proposal as a PI with reference to sections A6.2 and A6.3 of the Funding Rules.)
Do you hold a remunerated appointment at an Eligible Organisation?

Justification of PI status

D16. Eligibility - Relevant Organisation for this Proposal

(Enter the Organisation that is relevant to your participation on this Proposal, and that you will be associated with as at the Funding Commencement Date. The 'relevant organisation' is the primary organisation that will be supporting your involvement in this Project if it is funded. Note that the Organisation must be listed in D14 for this question to validate.)

Relevant Organisation

Griffith University

D17. What is your time commitment to this Project?

(Enter your time commitment to this Project as a Full-Time Equivalent (FTE). Note that a FTE of 1.0 represents a full-time commitment (i.e. 5 days per week).)

0.3

Part D - Personnel and ROPE (Prof Stephen Barnett)

D1. Personal Details

(To update personal details, click the 'Manage Personal Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Participation Type

Partner Investigator

Title

Prof

First Name

Stephen

Second Name

Mark

Family Name

Barnett

D4. Qualifications

(To update any qualifications, click on the 'Manage Qualifications' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Conferral Date	AQF Level	Degree/Award Title	Discipline/Field	Awarding Organisation	Country of Award
09/10/1985	Doctoral Degree	PhD	Physics	Imperial College, University of London	England
01/08/1982	Bachelor Honours Degree,Graduate Certificate, Graduate Diploma	BSc (with 1st class honours)	Physics	Imperial College, University of London	England

D5. Research Opportunity and Performance Evidence (ROPE) - Current and previous appointment(s) / position(s) - during the past 10 years

(To update any details in this table, click on the 'Manage Employment Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile. Refer to the Instructions to Applicants for more information.)

Description	Department	Contract Type	Employment Type	Start Date	End Date	Organisation
Royal Society Research Professor and Cargill Chair of Natural Philosophy	Physics and Astronomy	Permanent	Full Time	01/09/2013	20/02/2028	University of Glasgow, UK
Lecturer - Reader - Professor of Quantum Optics	Physics and Astronomy	Permanent	Full Time	01/10/1991	31/08/2013	University of Strathclyde, UK

D6. Research Opportunity and Performance Evidence (ROPE) - Academic Interruptions

(You must read the ROPE Statement http://www.arc.gov.au/arc-research-opportunity-and-performance-evidence-rope-statement before filling out this section.)

Have you experienced an interruption that has impacted on your academic record?

No

D7. Research Opportunity and Performance Evidence (ROPE) - Details of your academic career and opportunities for research, evidence of research impact and contributions to the field, including those most relevant to this Proposal

(Upload a PDF of no more than five A4 pages with details of your academic career and opportunities, evidence of research impact and contributions to the field.)

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D7. Research Opportunity and Performance Evidence (ROPE) - Career, opportunities and impact - PI Barnett

AMOUNT OF TIME AS AN ACTIVE RESEARCHER

I was awarded my PhD 32 years ago in 1985.

RESEARCH OPPORTUNITIES

Employment situation

SERC Postdoctoral Research Fellow, Imperial College. London, UK.	1985 – 1987	**1.0 FTE research**
Harwell - Wolfson Postdoctoral Research Fellow , AEA Harwell and Wolfson College Oxford, UK.	1987 – 1988	**1.0 FTE research**
GEC and the Fellowship of Engineering Research Fellow and Engineering Tutor at Somerville College, Oxford University, Oxford, UK.	1988 – 1990	**0.6 FTE research**
Lecturer in Physics, King's College, London, UK.	1990 – 1991	**0.4 FTE research**
Royal Society of Edinburgh and Scottish Office Education Department Research Fellow, University of Strathclyde, Glasgow, UK.	1991 – 1994	**1.0 FTE research**
Senior Lecturer then Reader, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, UK.	1994 – 1996	**0.4 FTE research**
Professor of Quantum Optics, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, UK.	1996 – 2013	**0.4 FTE research**
Royal Society of Edinburgh and Scottish Executive Education and Lifelong Learning Department Support Research Fellow, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, UK.	2001	**1.0 FTE research**
Royal Society Wolfson Research Merit Award Holder , Department of Physics and Applied Physics, University of Strathclyde, Glasgow, UK.	2007 – 2012	**0.6 FTE research**
Professor of Quantum Theory, University of Glasgow, Glasgow UK.	2013 – 2016	**0.6 FTE research**
Royal Society Research Professor and Cargill Chair of Natural Philosophy, University of Glasgow, Glasgow UK.	2016 – present	**1.0 FTE research**

Current Roles

I am a full-time Research Professor, with my position fully funded by the Royal Society. I am head of the Quantum Theory Group, which comprises at present, 3 faculty, 3 research fellows/RAs, 6 PhD students and

two academic visitors.

Research mentoring and facilities

I have had a rather diverse career including both some time in industry and academia and numerous research fellowships. I have supported myself through competitively won personal research fellowships or academic posts throughout my career, starting from immediately following the completion of my PhD. I spent most of my career at Strathclyde where I was a research fellow from 1991-1994 and became Professor of Quantum Optics in 1996 (at the age of 35). I moved across town to Glasgow University to found a new research group - the Quantum Theory Group.

RESEARCH ACHIEVEMENTS AND CONTRIBUTIONS

Prizes, honours and awards

1994: Maxwell Medal and Prize for Theoretical Physics by the Institute of Physics (The IoP's junior prize for theoretical physics).

1996: Elected FRSE (Fellow of the Royal Society of Edinburgh).

2006: Elected FRS (Fellow of the Royal Society).

2006: Quadrennial James Scott Prize Lectureship by the Royal Society of Edinburgh.

2007: Royal Society Wolfson Merit Award.

2011: Silver Medal of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague.

2013: Dirac Medal and Prize for Theoretical Physics by the Institute of Physics (The IoP's senior prize for theoretical physics).

2015: Medal of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague.

2016: Awarded Royal Society Research Professorship.

Research support income

I have held research grants continuously throughout my career.

Value of current grant portfolio: £1.57M (GBP).

Commercial outcomes such as patents, IP licences and resulting benefits

My research has not been aimed primarily at commercial outputs, but I have filed 4 distinct patents in my career, one of which is currently active and under development.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications

i. Publication context and contribution: Upload a PDF of no more than two pages. Provide clear information that explains the contribution and significance of your publications within the context of your discipline/s. This may include the importance/esteem of specific journals in your field; specific indicators of recognition within your field such as first authorship/citations.

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D8 ROPE – publication context and contribution – PI Barnett

With 333 journal articles across many fields of physics this is by no means an easy task. So I shall pick just a few highlights.

I am a theoretical physicist but my passion throughout my career has been to work on problems of concern to my many experimental colleagues. For me, it is at the interface between theory and experiment that many of the most interesting questions are to be found.

Above all, I enjoy grappling with fundamental and long-lived problems in physics. Nothing, in my research experience, quite matches the moment when a "crack" appears and I begin to see the light. There have been two occasions on which I have managed to solve long-standing problems in this way. The first was the discovery (with David Pegg) of the quantum mechanical operator that represents optical phase [1-4]; this was something that had been "proven" not to exist in the early 1960's and not seriously questioned thereafter, until our work. The Institute of Physics awarded me its Maxwell Medal and prize for this work. The second was the resolution of the so-called Abraham-Minkowski dilemma between the two rival forms for the momentum of light in a medium which has been disputed since 1909. Is it larger than the free-space value (as Minkowski would contend) or smaller (as suggested by Abraham)? The resolution is, in fact, beguilingly simple [5]. I was awarded the Dirac Medal and prize for this work by the Institute of Physics.

It is not possible, or indeed desirable, to pursue a programme of research based only on long-standing conundra, not least because of the time taken to make progress and the highly speculative, not to say, ambitious goal of solving them. I have always found it helpful, however, to have a big goal in mind when pursuing my research.

A few topics to which I have made strong (and highly cited) contributions *in addition to the phase and optical momentum* mentioned above are:

Optical Angular Momentum

A light beam carries spin angular momentum about its axis of propagation if it is circularly polarized. That it can also carry orbital angular momentum was realised more than 25 years ago. In working in this field I have been singularly fortunate in forming a close and lasting collaboration with Miles Padgett at Glasgow University. His experimental skill together with my own theoretical input has produced a combined expertise in this area that is probably without equal.

My contributions to this field of research include addressing the fundamental question of separating the spin and orbital parts of the optical angular momentum [6,7] and, very much in collaboration with Miles, a number of tests of angular momentum entanglement and the associated non-local quantum correlations [8-10]. It has also led me and my team, through our enhanced understanding of helicity, toward chemical physics, to explore interactions of light with chiral molecules. Highlights include our experimental verification [11] of the uncertainty relation for angular momentum and angle that I derived with David Pegg fourteen years earlier [4], and our prediction and demonstration of the Einstein-Podolsky-Rosen paradox for angle and angular momentum [12].

Quantum Information

I started working in quantum information at an early stage, both in my career and, indeed, in the development of the field. The main component of my efforts in this area since moving to Scotland has been in the study of so-called generalized measurements.

The description of quantum measurements that appears in most textbooks does not suffice to describe most real observations nor, indeed, to find the best possible measurements to perform in any given situation. A simple change (which amounts to dropping the requirement that distinct measurement outcomes correspond to orthogonal projectors) provides the necessary generalization [13]. With this technique my colleagues and I have determined the best possible measurements that are allowed for the extraction of information in a number of situations, motivated by quantum communications [14]. We also performed the first experiments designed to realise optimal measurements for discriminating between quantum states [15-17].

[1] D.T. Pegg and S.M. Barnett, Europhys. Lett. **6**, 483 (1988).
[2] S.M. Barnett and D.T. Pegg, J. Mod. Opt. **36**, 7 (1989).
[3] D.T. Pegg and S.M. Barnett, Phys. Rev. A **39**, 1665 (1989).
[4] S. M. Barnett and D.T. Pegg, Phys. Rev. A **41**, 3427 (1990).
[5] S. M. Barnett, Phys. Rev. Lett. **104**, 070401 (2010).
[6] S. M. Barnett, J. Opti. B: Quant. Semiclass. Opt. **4**, S7 (2002).
[7] S. M. Barnett, J. Mod. Opt. **57**, 1339 (2010).
[8] B. Jack, J. Leach, J. Romero, S. Franke-Arnold, M. Ritsch-Marte, S. M. Barnett and M. J. Padgett, Phys. Rev. Lett. **103**, 083602 (2009).
[9] A. K. Jha, J. Leach, B. Jack, S. Franke-Arnold, S. M. Barnett, R. W. Boyd and M. J. Padgett, Phys. Rev. Lett. **104**, 010501 (2010).
[10] J. Romero, J. Leach, B. Jack, M. R. Dennis, S. Franke-Arnold, S. M. Barnett and M. J. Padgett, Phys. Rev. Lett. **106**, 100407 (2011).
[11] S. Franke-Arnold, S. M. Barnett, E. Yao, J. Leach, J. Courtial and M. Padgett, New J. Phys. **6**, 103 (2004).
[12] J. Leach, B. Jack, J. Romero, A. K. Jha, A. M. Yao, S. Franke-Arnold, D. G. Ireland, R. W. Boyd, S. M. Barnett and M. J. Padgett, Science **329**, 662 (2010).
[13] S. M. Barnett, *Quantum information* (Oxford University Press, Oxford, 2009).
[14] S. M. Barnett and S. Croke, Adv. Opt. Phot. **1**, 238 (2009).
[15] R. B. M. Clarke, A. Chefles, S. M. Barnett and E. Riis, Phy. Rev. A **63**, 040305(R) (2001).
[16] R. B. M. Clarke, V. M. Kendon, A. Chefles, S. M. Barnett, E. Riis and M. Sasaki, Phys. Rev. A **64**, 012303 (2001).
[17] P. J. Mosley, S. Croke, I. A, Walmsley and S. M. Barnett, Phys. Rev. Lett. **97**, 193601 (2006).

ii. Publication list: Upload a PDF of no more than five pages. List your publications most relevant to this proposal categorised under the following headings: Authored books; Edited books; Book chapters; Referred Journal articles; Fully refereed conference proceedings; Other publication outputs. CVs and theses should not be included in this list. Next to each, provide the Project ID and years funded for any ARC grant on which you were a CI or Fellow from which the item originated.

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D8. ROPE – Publication List – PI Barnett

Authored Books

1) *Methods in Theoretical Quantum Optics*, Stephen M. Barnett and Paul M. Radmore (Oxford University Press, Oxford, 1997).

2) *Quantum Information,* Stephen M. Barnett (Oxford University Press, Oxford, 2009).

3) *Phase Space Methods for Degenerate Quantum Gases*, Bryan J. Dalton, John Jeffers and Stephen M. Barnett (Oxford University Press, Oxford, 2015).

Edited Books

4) S.M. Barnett and J.A. Vaccaro, Editors, "The Quantum Phase Operator: A Review" (Taylor and Francis, London, 2007) ISBN 9781584887607.

Book Chapters n/a

Referred Journal articles

333 research articles in refereed international journals, starting in 1984, the most recent of which are:

5) *Spatial Schmidt modes generated in parametric down-conversion*, F. M. Miatto, H. Di Lorenzo Pires, S. M. Barnett and M. P. van Exter; European Physical Journal D **66**, 263 (2012).

6) *Electric-magnetic symmetry and Noether's theorem*, Robert P. Cameron and Stephen M. Barnett; New Journal of Physics **14**, 123019 (2012).

6) *Measurement-driven dynamics for a coherently-excited atom*, Andrew J. T. Colin, Stephen M. Barnett and John Jeffers; Journal of Modern Optics **59**, 1803 (2012).

7) *Comment on "Trouble with the Lorentz Law of Force: Incompatibility with Special Relativity and Momentum Conservation"*, Stephen M. Barnett; Physical Review Letters **110**, 089402 (2013).

8) *Optical Activity in Twisted Solid-Core Photonic Crystal Fibers*, X. M. Xi, T. Weiss, G. K. L. Wong, F. Biancalana, S. M. Barnett, M. J. Padgett and P. St. J. Russell; Physical Review Letters **110**, 143903 (2013).

9) *Grassmann phase space theory and the Jaynes-Cummings model*, B. J. Dalton, B. M. Garraway, J. Jeffers and S. M. Barnett; Annals of Physics **334,** 100 (2013).

10) *Detection of a Spinning Object Using Light's Orbital Angular Momentum*, Martin P. J. Lavery, Fiona C. Speirits, Stephen M. Barnett and Miles J. Padgett; Science **341**, 537 (2013).

11) *Security of high-dimensional quantum key distribution protocols using Franson interferometers*, Thomas Brougham, Stephen M. Barnett, Kevin T. McClusker, Paul G. Kwiat and Daniel J. Gauthier; Journal of Physics B: Atomic, Molecular and Optical Physics **46**, 104010 (2013).

12) *Tailored two-photon correlation and fair sampling: a cautionary tale*, J. Romero, D. Giovannini, D. S. Tasca, S. M. Barnett and M. J. Padgett; New Journal of Physics **15**, 083047 (2013).

13) *Do Waves Carrying Orbital Angular Momentum Possess Azimuthal Linear Momentum?*, Fiona C. Speirits and Stephen M. Barnett; Physical Review Letters **111**, 103602 (2013).

14) *Superweak momentum transfer near optical vortices*, Stephen M. Barnett and M. V. Berry; Journal of Optics **15**, 125701 (2013).

15) *Topological Zeeman effect and circular birefringence in twisted photonic crystal fibers*, T. Weiss, G. K. L. Wong, F. Biancalana, S. M. Barnett, X. M. Xi and P. St.J. Russell; Journal of the Optical Society of America B **30**, 2921 (2013).

16) *Beyond Landauer Erasure*, Stephen M. Barnett and Joan A. Vaccaro; Entropy **15**, 4956 (2013).

17) *Quantum Optical State Comparison Amplifier*, Electra Eleftheriadou, Stephen M. Barnett and John Jeffers; Physical Review Letters **111**, 213601 (2013).

18) *Mutually unbiased measurements for high-dimensional time-bin-based photonic state*s, Thomas Brougham and Stephen M. Barnett; Europhysics Letters **104**, 30003 (2013).

19) *Disciminatory optical force for chiral molecules*, Robert P. Cameron, Stephen M. Barnett and Alison M. Yao; New Journal of Physics **16**, 013020 (2014).

20) *Maxwellian theory of gravitational waves and their mechanical properties*, Stephen M. Barnett; New Journal of Physics **16**, 023027 (2014).

21) *Optical helicity of interfering waves*, Robert P. Cameron, Stephen M. Barnett and Alison M. Yao; Journal of Modern Optics **61**, 25 (2014).

22) *Molecules in the mirror: how SERS backgrounds arise from the quantum method of images*, Stephen M. Barnett, Nadine Harris and Jeremy J. Baumberg; Physical Chemistry and Chemical Physics **16**, 6544 (2014).

23) *Quantum probability rule: a generalization of the theorems of Gleason and Busch*, Stephen M. Barnett, James, D. Cresser, John Jeffers and David T. Pegg; New Journal of Physics; **16**, 043025 (2014).

24) *Optical angular momentum in a rotating frame*. Fiona C. Speirits, Martin P. J. Lavery, Miles J. Padgett and Stephen M. Barnett; Optics Letters, **39**, 2994 (2014).

25) *Diffraction Gratings for Chiral Molecules and Their Applications*, Robert P. Cameron, Alison M. Yao and Stephen M. Barnett; The Journal of Physical Chemistry A **118**, 3472 (2014).

26) *Rotational Doppler velocimetry to probe the angular velocity of spinning microparticles*, D. B. Phillips, M. P. Lee, F. C. Speirits, S. M. Barnett, S. H. Simpson, M. P. J. Lavery, M. J. Padgett and G. M. Gibson; Physical Review A **90**, 011801(R) (2014).

27) *Observation of the rotational Doppler shift of a white-light, orbital-angular-momentum-carrying beam backscattered from a rotating body*, Martin P. J. Lavery, Stephen M. Barnett, Fiona C. Speirits and Miles J. Padgett; Optica **1**, 1 (2014).

28) *Optical Dirac equation*, Stephen M. Barnett; New journal of Physics **16**, 093008 (2014).

29) *Entropic uncertainty minimum for angle and angular momentum*, Alison M. Yao, Thomas Brougham, Electra Eleftheriadou, Miles J. Padgett and Stephen M. Barnett; Journal of Optics **16**, 105404 (2014).

30) *Cavity-enabled high-dimensional quantum key distribution*, Thomas Brougham and Stephen M. Barnett; Journal of Physics B: Atomic, Molecular and Optical Physics **47**, 155501 (2014).

31) *Two-particle multi-mode interference*, Geregly Ferenczi, Václav Potoček and Stephen M. Barnett; Journal of Optics **16**, 105710 (2014).

32) *Optical activity in the scattering of structured light*, Robert P. Cameron and Stephen M. Barnett; Physical Chemistry and Chemical Physics **16**, 25819 (2014).

33) *Is the angular momentum of an electron conserved in a uniform magnetic field?*, Colin R. Greenshields, Robert L. Stamps, Sonja Franke-Arnold and Stephen M. Barnett; Physical Review Letters **113**, 240404 (2014).

34) *Stability of point spectrum for three-dimensional quantum walks on a line*, M. Štefaňák, I. Brezdekova, I. Jex and S. M. Barnett; Quantum Information and Computation **14**, 1213 (2014).

35) *Spatially structured photons that travel in free space slower than the speed of light*, Daniel Giovannini, Jacqueline Romero, Václav Potoček, Gergely Ferenczi, Fiona Speirits, Stephen M. Barnett, Daniele Faccio and Miles J. Padgett; Science **347**, 857 (2015).

36) *Experimental Implementation of a Quantum Optical State Comparison Amplifier*, Ross J. Donaldson, Robert J. Collins, Electra Eleftheriadou, Stephen M. Barnett, John Jeffers and Gerald S. Buller; Physical Review Letters **114**, 120505 (2015).

37) *Spatially Dependent Electromagnetically Induced Transparency*, N. Radwell, T. W. Clark, B. Piccirillo, S. M. Barnett and S. Franke-Arnold; Physical Review Letters **114**, 123603 (2015)

38) *On the exponential form of the displacement operator for different systems*, Václav Potoček and Stephen M. Barnett; Physica Scripta **90**, 06508 (2015).

39) *Theory of radiation pressure on magneto-dielectric materials*, Stephen M. Barnett and Rodney Loudon; New Journal of Physics **17**, 063027 (2015).

40) *Generalized ray optics and orbital angular momentum carrying beams*, Václav Potoček and Stephen M. Barnett; New Journal of Physics **17**, 103034 (2015).

41) *The azimuthal component of Poynting's vector and the angular momentum of light*, Robert P. Cameron, Fiona C. Speirits, Claire Gilson, L. Allen and Stephen M. Barnett; Journal of Optics **17**, 125610 (2015).

42) *Image retrodiction at low light levels*, Matthias Sonnleitner, John Jeffers and Stephen M. Barnett; Optica **2**, 950 (2015).

43) *Energy conservation and the constitutive relations in chiral and non-reciprocal media*, Stephen M. Barnett and Robert P. Cameron; Journal of Optics **18**, 015404 (2016).

44) *Grassmann phase space methods for fermions. I. Mode theory*, B. J. Dalton, J. Jeffers and S. M. Barnett; Annals of Physics **370**, 12 (2016).

45) *On the natures of the spin and orbital parts of optical angular momentum*, Stephen M. Barnett, L. Allen, Robert P. Cameron, Claire R. Gilson, Miles J. Padgett, Fiona C. Speirits and Alison M. Yao; Journal of Optics **18**, 064004 (2016).

46) *Reply to Comment on 'Energy conservation and the constitutive relations in chial and non-reciprocal media'*, Stephen M. Barnett and Robert P. Cameron; Journal of Optics **18**, 068002 (2016).

47) *Matter-wave grating distinguishing conservative and dissipative interactions*, Robert P. Cameron, Jörg B. Götte, Stephen M. Barnett and J. P. Cotter; Physical Review A **94**, 013604 (2016).

48) *Chiral rotational spectroscopy*, Robert P. Cameron, Jörg B. Götte and Stephen M. Barnett; Physical Review A **94**, 032505 (2016).

49) *The information of high-dimensional time-bin encoded photons*, Thomas Brougham, Christoph F. Wildfeuer, Stephen M. Barnett and Daniel J. Gauthier; European Physical Journal D **70**, 214 (2016).

50) *Optical orbital angular momentum*, Stephen M. Barnett, Mohamed Babiker and Miles J. Padgett; Philosophical Transactions of the Royal Society A **375**, 20150444 (2017).**316)** *Chirality and the angular momentum of light*, Robert P. Cameron, Jörg B. Götte, Stephen M. Barnett and Alison M. Yao; Philosophical Transactions of the Royal Society A **375**, 20150433 (2017).

51) *Difficulty of distinguishing product states*, Sarah Croke and Stephen M. Barnett; Physical Review A **95**, 012337 (2017).

52) *Will a decaying atom feel a friction force?*, Matthias Sonnleitner, Nils Trautmann and Stephen M. Barnett; Physical Review Letters **118**, 053601 (2017).

53) *Grassmann phase space methods for fermions. II. Field theory*, B. J. Dalton, J. Jeffers and S. M. Barnett; Annals of Physics **377**, 268 (2017).

54) *From retrodiction to Bayesian quantum imaging*, Fiona C. Speirits, Matthias Sonnleitner and Stephen M. Barnett; Journal of Optics **19**, 04401 (2017).

55) *Relativistic Electron Vortices*, Stephen M. Barnett; Physical Review Letters; **118**, 114802 (2017).

56) *Programmable holographic technique for implementing unitary and nonunitary transformations*, Yu Wang, Václav Potoček, Stephen M. Barnett and Xue Feng; Physical Review A **95**, 033827 (2017).

57) *Adaptive foveated single-pixel imaging with dynamic supersampling*, David B. Phillips, Ming-Jie Sun, Jonathan M. Taylor, Matthew P. Edgar, Stephen M. Barnett, Graham M. Gibson and Miles J. Padgett; Science Advances **3**, 1601782 (2017).

58) *Holographic quantum imaging: reconstructing spatial properties via two-particle interference*; Nils Trautmann, Geregly Ferenczi, Sarah Croke and Stephen M. Barnett; Journal of Optics **19**, 054005 (2017).

59) *Optimal sequential measurements for bipartite state discrimination*, Sarah Croke, Stephen M. Barnett and Graeme Weir; Physical Review A **95**, 052308 (2017).

60) *Grassmann phase space theory for fermions*, Bryan J. Dalton, John Jeffers and Stephen M. Barnett; Fortschritte der Physik **65**, 1600038 (2017).

61) *Proposed optical realization of a two photon four-qubit entangled χ state*, Atirach Ritboon, Sarah Croke and Stephen M. Barnett; Journal of Optics **19**, 075201 (2017).

62) *Barnett Replies (to Comment on "Relativsitic Electron Vortices")*; Stephen M. Barnett; Physical Review Letters **119**, 029502 (2017).

63) *Journeys from quantum optics to quantum technology*, Stephen M. Barnett, Almut Beige, Artur Ekert, Barry M. Garraway, Christoph H. Keitel, Viv Kendon, Manfred Lein, Gerard J. Milburn, Hector M. Moya-Cessa, Mio Murao, Jiannis K. Pachos, Massimo Palma, Emmanuel Paspalakis, Simon J. D.

Phoenix, Bernard Piraux, Martin B. Plenio, Barry C. Sanders, Jason Twamley, A. Vidiella-Barenco and M. S. Kim; Progress in Quantum Electronics; **54**, 19 (2017).

64) *Optimal discrimination of single-qubit mixed states*, Graeme Weir, Stephen M. Barnett and Sarah Croke; Physical Review A **96**, 022312 (2017).

65) *Gleason-Busch theorem for sequential measurements*, Kieran Flatt, Stephen M. Barnett and Sarah Croke; Physical Review A **96**, 062125 (2017).

66) *The Röntgen interaction and forces on dipoles is time-modulated optical fields*, Matthias Sonnleitner and Stephen M. Barnett; European Physical Journal D **71**, 336 (2017).

67) *Vacuum friction*, Stephen M. Barnett and Matthias Sonnleitner; Journal of Modern Optics **65**, 23 (2018).

Fully refereed conference procedures n/a

Other publication outputs n/a

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs

(Upload a PDF of no more than three A4 pages with a list of your ten career-best academic research outputs related to the Proposal.)

Uploaded PDF file follows on next page.

D9 ROPE – 10 career best research outputs – PI Barnett

Total career citations (Google Scholar): **22,811**. The citation numbers quoted below for individual articles are also from this source.

1) *Free-space information transfer using light beams carrying orbital angular momentum*, G. Gibson, J. Courtial, M.J. Padgett, M. Vasnetsov, V. Pas'ko, S. M Barnett, S. Franke-Arnold; Optics express **12,** 5448-5456 (2004).

1,457 citations

Shows that information encoded in orbital angular momentum states of a light is resistant to eavesdropping in the periphery of the beam.

2) *Phase Properties of the Quantized Single-Mode Electromagnetic Field,* D.T. Pegg and S.M. Barnett; Physical Review A **39**, 1665 (1989).

979 citations

Introduced a new description of the phase of optical fields that eluded Dirac 60 years earlier. It has become known as the "Pegg-Barnett" phase formalism.

3) *Measuring the Orbital Angular Momentum of a Single Photon*, J. Leach, M.J. Padgett, S.M. Barnett, S. Franke-Arnold and J. Courtial, Physical Review Letters; **88**, 257901 (2002).

761 citations

Proposes an interferometric method for measuring the orbital angular momentum of single photons which has had applications for entanglement experiments, quantum cryptography and high density information transfer.

4) *Unitary Phase Operator in Quantum Mechanics*, D.T. Pegg and S.M. Barnett; Europhysics Letters **6**, 483 (1988).

717 citations

Defined an operator that represents the phase of an optical field mode which, unlike previous attempts, attributed uniform random phase uncertainty to the vacuum.

5) *On the Hermitian Optical Phase Operator,* S.M. Barnett and D.T. Pegg; Journal of Modern Optics **36**, 7 (1989).

610 citations

Introduced the operator that has become widely accepted as the phase observable of a single mode optical field.

6) *Quantization of the Electromagnetic Field in Dielectrics,* B. Huttner and S.M. Barnett; Physical Review A **46**, 4306 (1992).

503 citations

Defines the quantum electromagnetic field in dispersive and lossy linear dielectrics using a microscopic treatment of the dielectric medium. It justifies phenomenological models of light propagation used in quantum optics.

7) *Orbital Angular Momentum and Nonparaxial Light Beams,* S.M. Barnett and L. Allen; Optics Communications, **110**, 670 (1994).

322 citations

Showed that the separation of the angular momentum into spin and orbital components are general and independent of the paraxial approximation for a general monochromatic beam with near cylindrical symmetry.

8) *Squeezing and Superposition States*, K. Wodkiewicz, P.L. Knight, S.J. Buckle and S.M. Barnett; Physical Review A **35**, 2567 (1987).

320 citations

Showed squeezed states of light can be produced by resonant interaction with prepared atoms. Opened the door to a new regime for studying squeezed states far beyond that previously imagined.

9) *Quantum Correlations in Optical Angle-Orbital Angular Momentum Variables*, J. Leach, B. Jack, J. Romero, A.K. Jha, A.M. Yao, S. Franke-Arnold, D. G. Ireland, R. W. Boyd, S.M. Barnett and M.J. Padgett; Science **329**, 662 (2010).

300 citations

10) *Resolution of the Abraham-Minkowski Dilemma*, S.M. Barnett; Physical Review Letters **104**, 070401 (2010).

271 citations

This paper gives a resolution of the century-old Abraham–Minkowski dilemma of the nature of optical momentum in a medium.

D10. Research Opportunity and Performance Evidence (ROPE) - Currently held ARC Projects

(This information is auto-populated from your RMS profile and will include any current Project which has not yet had a Final Report approved and the Project file closed by the ARC. If you have any concerns with the information recorded here, contact your Administering Organisation's Research Office.)

Identifier	Investigators	Admin Organisation	Project Title	Funding	End Date	Final Report Due Date	Final Report Status
LP140100797	Prof Joan Vaccaro ; Dr Luke Uribarri ; Prof Stephen Barnett ; Dr Erik Streed	Griffith University	Lightweight battery with more yield than a tonne of coal	$255,409	13/11/2018	13/11/2019	Draft

D11. Eligibility - Role of Partner Investigator

(Please indicate which of the Partner Investigator role options from A6.3.3 of the Funding Rules apply to your role on this Project. Select all options that apply.)

Have the experience and capacity to provide effective supervision support and mentoring of research personnel associated with the Project in their areas of expertise.
Have demonstrated the relevant skills and experience to effectively manage a similar scale research Project.

D12. Eligibility - Will you be residing predominantly in Australia for the Project Activity Period?

(This is a 'Yes' or 'No' question. Indicate whether you will be residing predominantly in Australia for the Project Activity Period. If you are applying as a CI and you answer 'No' to this question you will be prompted to contact your Research Office to check your eligibility. If you are a Foreign National, you must reside legally in Australia. Eligibility will be based solely on the information contained in this Proposal.)

No

D13. Eligibility - Are you currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date?

(This is a 'Yes' or 'No' question. If you are applying as a CI and your answer is 'Yes' to this question you will be prompted to contact your Research Office. Eligibility will be based solely on the information contained in this Proposal.)

No

D14. Eligibility - Employment Details as at Funding Commencement Date of Project

(This question will be used to determine your eligibility. Your eligibility will be based solely on the information contained in this Proposal. Confirm your employment status at all organisations that you will be associated with as at the Funding Commencement Date. Enter the relevant appointment type and Full-Time Equivalent (FTE) for each organisation.)

Org name	Is this an Eligible Organisation?	Please choose your appointment type for this organisation.	Please enter your FTE for this Organisation
University of Glasgow, UK		Employee	1

D15. Eligibility - Further Details Regarding Partner Investigator Status - Do you hold a remunerated appointment at an Eligible Organisation?

(At A2 Partner Investigator has been selected as the role type, but it appears that the participant meets the criteria of a Chief Investigator.
NOTE: this question is mandatory ONLY FOR PIs WHO:
• at D12 confirmed that they will reside predominantly in Australia for the Project Activity Period of the proposed Project; AND
• at D13 confirmed that they are not currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date; AND
• at D14 indicated that they would hold either:
- an appointment at an Eligible Organisation equal or greater than 0.2 FTE; OR
- an emeritus appointment at an Eligible Organisation

This is a 'Yes' or 'No' question. If you select 'Yes', you will be further prompted to justify your participation on this Proposal as a PI with reference to sections A6.2 and A6.3 of the Funding Rules.)
Do you hold a remunerated appointment at an Eligible Organisation?

Justification of PI status

D16. Eligibility - Relevant Organisation for this Proposal

(Enter the Organisation that is relevant to your participation on this Proposal, and that you will be associated with as at the Funding Commencement Date. The 'relevant organisation' is the primary organisation that will be supporting your involvement in this Project if it is funded. Note that the Organisation must be listed in D14 for this question to validate.)

Relevant Organisation

University of Glasgow, UK

D17. What is your time commitment to this Project?

(Enter your time commitment to this Project as a Full-Time Equivalent (FTE). Note that a FTE of 1.0 represents a full-time commitment (i.e. 5 days per week).)

0.1

Part D - Personnel and ROPE (Dr Luke Uribarri)

D1. Personal Details

(To update personal details, click the 'Manage Personal Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Participation Type

Partner Investigator

Title

Dr

First Name

Luke

Second Name

Alexander

Family Name

Uribarri

D4. Qualifications

(To update any qualifications, click on the 'Manage Qualifications' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile.)

Conferral Date	AQF Level	Degree/Award Title	Discipline/Field	Awarding Organisation	Country of Award
15/08/2008	Doctoral Degree	Doctor of Philosophy	Aerospace and Mechanical Engineering	Princeton University	United States of America
01/06/2005	Masters Degree	Master of Arts	Aerospace and Mechanical Engineering	Princeton University	United States of America
16/05/2003	Bachelor Degree	Bachelor of Science	Aerospace Engineering / Astronautics	University of Southern California	United States of America

D5. Research Opportunity and Performance Evidence (ROPE) - Current and previous appointment(s) / position(s) - during the past 10 years

(To update any details in this table, click on the 'Manage Employment Details' link below. Note this will open a new browser tab. When returning to the form ensure you 'Refresh' the page to capture the changes made to your profile. Refer to the Instructions to Applicants for more information.)

Description	Department	Contract Type	Employment Type	Start Date	End Date	Organisation
Deputy to the Chief Scientist in matters of program management, technical advisory, and technology transfer	Corporate Engineering and Technology	Permanent	Full Time	15/08/2008		Lockheed Martin (US)

D6. Research Opportunity and Performance Evidence (ROPE) - Academic Interruptions

(You must read the ROPE Statement http://www.arc.gov.au/arc-research-opportunity-and-performance-evidence-rope-statement before filling out this section.)
Have you experienced an interruption that has impacted on your academic record?

No

D7. Research Opportunity and Performance Evidence (ROPE) - Details of your academic career and opportunities for research, evidence of research impact and contributions to the field, including those most relevant to this Proposal

(Upload a PDF of no more than five A4 pages with details of your academic career and opportunities, evidence of research impact and contributions to the field.)

Uploaded PDF file follows on next page.

D7 Research Opportunity and Performance Evidence (ROPE) – Career, opportunities and impact- PI Urbarri

AMOUNT OF TIME AS AN ACTIVE RESEARCHER

I was awarded my PhD 10 years ago, in 2008.

RESEARCH OPPORTUNITIES

I have been employed at Lockheed Martin since graduating in 2008, first as a Senior Aeronautical Engineer in the "Skunk Works" division and later as a Project Manager and Deputy to the Chief Scientist in the corporate Chief Scientist's Office. This has provided excellent—even unique—opportunities for research, research management, and technological development. Lockheed Martin creates breakthrough technologies in air, land, and sea vehicles, and has been responsible for developing iconic aircraft including the U-2, the F-117 Nighthawk, the F-22 Raptor, and most recently the F-35 Joint Strike Fighter. However, by contrast to academic research, this industry research is technology driven and is generally not published openly.

I am currently a Staff Aeronautical Engineer and Deputy to the Chief Scientist at Lockheed Martin. Currently and over the past ten years, my responsibilities are split approximately 35/25/35/5 between research management, technology transfer and commercialization, research, and teaching. Prior to that as a PhD student, my primary responsibility was to undertake academic research.

Lockheed Martin is one of the world's largest technology companies, with turnover of $50 billion dollars in 2017. It is also the world's largest defence contractor. The Skunk Works and the Chief Scientist's Office (CSO) are premier research arms of Lockheed, with the freedom to undertake blue-sky research as well as practical applications. Skunk Works and CSO have relatively unfettered access to the extensive research infrastructure and expertise of the organisation; including world-class capabilities in conceptual design, nanofabrication facilities and expertise, systems engineering and integration, complex project management, software development and rapid prototyping. The Aeronautics Division houses a range of laboratories, including Aircraft Systems Test Labs, Materials and Processing Labs, Human Immersive Labs, Composites and Adhesives Labs, a Rapid Prototyping Center, a Flight Test Instrumentation Lab, Structural Test Labs, and Wind Tunnel Test Labs. Similar and extensive test and instrumentation facilities are available around the corporation, in the US, UK, Canada, and Australia. Lockheed Martin's extensive research relationships with global universities has given us access to dozens of the best research laboratories in the world in many engineering and applied physics fields. Lockheed Martin also sponsors external development courses. I have benefited from this, attending courses in aircraft design, pulsed power electronics, quantum information science, and even contract law.

Although the environment for research and technological innovation at Lockheed Martin is excellent, much of the R&D undertaken by the company is classified or commercial in-confidence. This limits my ability to fully explicate my R&D contributions within this application.

RESEARCH ACHIEVEMENTS AND CONTRIBUTIONS

Honours and Awards

Throughout my academic and professional career, I have been frequently recognised with awards and honours.

2011 Spot Award, Lockheed Martin. Recognizes exemplary performance.

2011 Group Special Recognition Award, Lockheed Martin. Acknowledges extraordinary performance throughout the year by individuals and teams.

2010 Special Recognition Award, Lockheed Martin. Acknowledges extraordinary performance throughout the year by individuals and teams.

2007 Wallace Memorial Fellowship, Princeton University. One-year fellowship awarded annually to two members of the Princeton University Graduate School for academic distinction

2006 Luigi Crocco Prize for Excellence in Teaching, Princeton University

2004 Sayre Graduate Prize, Princeton University. For outstanding performance in both research and course work.

2003 Upton Fellowship, Princeton University. The highest honour given to an incoming engineering graduate student. Provides tuition, support, and expenses.

2003 National Defense Science and Engineering Graduate Fellowship, Air Force Office of Scientific Research. Nationally competitive three-year fellowship awarded to about 200 students annually. Provides full tuition and support.

2001 Barry Goldwater Scholarship, Barry Goldwater Foundation. Nationally competitive scholarship awarding the potential and plans for higher education and a future in science

2000 National Merit Scholarship
1999 USC Presidential Scholarship, University of Southern California

Invited Keynotes and Addresses

Invited talks at internal and external conferences in the last ten years have included (but were not limited to)

- US Air Force Chief Scientist's Global Horizons panel (2013)
- Lockheed Martin Technical Leadership Conference (2014)
- US Air Force Research Laboratory symposium (2014)
- AIAA Hypersonics and Space Planes Conference (2015)
- Our Quantum Future panel (QSCITECH, eQus) (2015)

Research Support and Outcomes

Through my efforts, LM has secured $7M in contract funding from 2011 to the present; LM-funded projects I have led have received an additional ~$3M in matching support from government research organizations in the US, Canada, the UK, Australia, and Europe. I hold two granted patents with two additional pending.

Research and development efforts

In my role at Lockheed, I am responsible for developing both internal and external research projects, and managing them through the research and development phase towards useful products. I currently facilitate several projects in the US, Australia, Canada, New Zealand, and the UK in the following areas:

- Flight-hardened optical spectroscopy
- Quantum control and quantum thermodynamics
- Ceramic electronics
- Chemical lasers
- Computational fluid dynamics, and
- Hypersonic flight

In the past, I have overseen internal LM competitions for seed-project funding, and worked the transition from seed projects to useful products. The projects that I lead have high visibility within Lockheed Martin, with personnel from across the company expecting to leverage the results in end products. I expect this Linkage Project to be of particular interest to our LM energy security portfolios.

Research in aerospace engineering

I completed a PhD at Princeton University, receiving many honours, in the area of low-earth orbit and deep-space engineering, with a focus on plasma physics and spacecraft propulsion---such applied physics being an essential component of this Linkage project. The specific area of my PhD was propulsion systems to maneuver satellites and spacecraft. I developed and evaluated mathematical models for plasma-electrode interactions in plasma thrusters for comparison with experimental data; devised and implemented plasma thruster experiments, including mechanical and electrical design; and developed automation software for experiment control and data analysis, for invasive probing and optical diagnostics. Apart from journal publications and conference presentations, the relevance of my work to industry was recognised by Boeing, the Air Force Research Lab, and LM; all of whom I have worked closely with.

Academic Experience

In 2011, whist maintaining a full-time position at Lockheed Martin, I was an Adjunct Professor at George Washington University, where I taught graduate-level coursework in the Aerospace and Mechanical Engineering department, and counseled students about career opportunities in academia and industry. I also taught undergraduate and graduate level courses on engineering

design methods, spacecraft dynamics, orbital mechanics, fluid mechanics, and experimental methods whilst undertaking my PhD at Princeton. The quality of my teaching at Princeton was recognised by the Luigi Crocco Prize for Excellence in Teaching in 2006.

Technical skills

Apart from expertise in aerospace engineering, research management, and commercialization, I have a range of technical skills that will be useful to this project. I am fluent in ten programming languages, and more than ten engineering design software packages; and have a range of experience in laboratory based research in optics, electronics, and mechanical engineering.

D8. Research Opportunity and Performance Evidence (ROPE) - Publications

i. Publication context and contribution: Upload a PDF of no more than two pages. Provide clear information that explains the contribution and significance of your publications within the context of your discipline/s. This may include the importance/esteem of specific journals in your field; specific indicators of recognition within your field such as first authorship/citations.

Uploaded PDF file follows on next page.

D8. Research Opportunity and Performance Evidence (ROPE) – Publications- PI Urbarri

i. Publication context and contribution

Academic publications are not of direct relevance to my role in this Linkage project, with my main responsibilities being to provide leadership in technology development and transfer. For completeness I include a list below. However, of much more relevance, I regularly prepare internal Lockheed Martin technology white papers. White papers of this kind will be important to the project, communicating the results across Lockheed, and to specialists who can provide development expertise, and greatly assisting the overall technology transfer process. Although many Lockheed white papers are classified or commercial in-confidence, I have written white papers and reports on topics such as:

- Space debris cleanup
- Development of advanced aerospace ceramic materials
- Extraction techniques for recovery of valuable mineral resources from seawater
* - Energy storage systems based on quantum thermodynamics
- Laboratory techniques for measuring impedance of time-varying electrical loads
* - Non-linear optical properties of quantum dots
- New types of chemical lasers
- Unmanned aerial vehicles (UAV)

I have also filed patents in the areas of thermal management on aerospace vehicles, and energy storage using quantum coherence (the topic of this grant application).

ii. Publication list: Upload a PDF of no more than five pages. List your publications most relevant to this proposal categorised under the following headings: Authored books; Edited books; Book chapters; Referred Journal articles; Fully refereed conference proceedings; Other publication outputs. CVs and theses should not be included in this list. Next to each, provide the Project ID and years funded for any ARC grant on which you were a CI or Fellow from which the item originated.

Uploaded PDF file follows on next page.

D8 Research Opportunity and Performance Evidence (ROPE) – Publications- CI Uribarri
ii. Publication List

Authored books n/a

Edited books n/a

Book chapters n/a

Refereed Journal articles

[1] Luke Uribarri and Edgar Y. Choueiri. Creation of Onset Voltage Hash by Anode Spots in a Magnetoplasmadynamic Thruster. Journal of Propulsion and Power, 25, 947-957 (2009).

[2] Luke Uribarri and Edgar Y. Choueiri. Relationship between anode spots and onset voltage hash in magnetoplasmadynamic thrusters. Journal of Propulsion and Power, 24, 571-577 (2008).

[3] Luke Uribarri and Edgar Y. Choueiri. Corruption of pulsed electric thruster voltage fluctuation measurements by transmission line resonances. Journal of Propulsion and Power, 24, 637-639 (2008).

Fully refereed conference proceedings

[4] Luke Uribarri and Edgar Y. Choueiri. The Onset of Voltage Hash and its Relationship to Anode Spots in Magnetoplasmadynamic Thrusters. IEPC-2005-084. Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005.

[5] Luke Uribarri and Edgar Y. Choueiri. Effects of Power Supply Resonances in Onset Studies of Quasi-Steady MPD Thrusters. EP-21: Electric Propulsion Diagnostics and Thrust Stand Development, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2007. Chapter DOI: 10.2514/6.2007-5295.

Other publication outputs

[6] Luke Uribarri and Edward H. Allen. "Electron Transpiration Cooling for Hot Aerospace Surfaces", 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference (2015)

[7] Edward H “Ned” Allen and Luke A. Uribarri. Advanced technology needs for new multifunctional materials with controlled functional nanostructure. Invited keynote presentation, Powdered and Porous Materials Conference (2013).

[8] Luke A. Uribarri. Onset voltage hash and anode spots in quasi-steady magnetoplasmadynamic thrusters. PhD Dissertation, Princeton University, 2008.

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs

(Upload a PDF of no more than three A4 pages with a list of your ten career-best academic research outputs related to the Proposal.)

Uploaded PDF file follows on next page.

D9. Research Opportunity and Performance Evidence (ROPE) - Ten career-best academic research outputs PI Uribarri

As discussed in Section D8, **academic publications are not directly relevant to my role as an industry partner** in this Linkage project. This section is therefore not applicable, as discussed in the ARC Linkage Grant instructions to applicants. For reference D8 details some of the written contributions I have made to research development, primarily in the form of white papers and patents I have prepared at Lockheed Martin as well as the academic publications I have co-authored. That list is duplicated below.

[1] Luke Uribarri and Edgar Y. Choueiri. Creation of Onset Voltage Hash by Anode Spots in a Magnetoplasmadynamic Thruster. Journal of Propulsion and Power, 25, 947-957 (2009).

[2] Luke Uribarri and Edgar Y. Choueiri. Relationship between anode spots and onset voltage hash in magnetoplasmadynamic thrusters. Journal of Propulsion and Power, 24, 571-577 (2008).

[3] Luke Uribarri and Edgar Y. Choueiri. Corruption of pulsed electric thruster voltage fluctuation measurements by transmission line resonances. Journal of Propulsion and Power, 24, 637-639 (2008).

[4] Luke Uribarri and Edgar Y. Choueiri. The Onset of Voltage Hash and its Relationship to Anode Spots in Magnetoplasmadynamic Thrusters. IEPC-2005-084. Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005.

[5] Luke Uribarri and Edgar Y. Choueiri. Effects of Power Supply Resonances in Onset Studies of Quasi-Steady MPD Thrusters. EP-21: Electric Propulsion Diagnostics and Thrust Stand Development, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2007. Chapter DOI: 10.2514/6.2007- 5295.

[6] Luke Uribarri and Edward H. Allen. "Electron Transpiration Cooling for Hot Aerospace Surfaces", 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference (2015)

[7] Edward H “Ned” Allen and Luke A. Uribarri. Advanced technology needs for new multifunctional materials with controlled functional nanostructure. Invited keynote presentation, Powdered and Porous Materials Conference (2013).

[8] Luke A. Uribarri. Onset voltage hash and anode spots in quasi-steady magnetoplasmadynamic thrusters. PhD Dissertation, Princeton University, 2008.

D10. Research Opportunity and Performance Evidence (ROPE) - Currently held ARC Projects

(This information is auto-populated from your RMS profile and will include any current Project which has not yet had a Final Report approved and the Project file closed by the ARC. If you have any concerns with the information recorded here, contact your Administering Organisation's Research Office.)

Identifier	Investigators	Admin Organisation	Project Title	Funding	End Date	Final Report Due Date	Final Report Status
LP140100595	Prof Warwick Bowen ; Dr Luke Uribarri	The University of Queensland	Optomechanical refrigeration of electronic circuits	$300,000	28/04/2018	28/04/2019	Draft
LP140100797	Prof Joan Vaccaro ; Dr Luke Uribarri ; Prof Stephen Barnett ; Dr Erik Streed	Griffith University	Lightweight battery with more yield than a tonne of coal	$255,409	13/11/2018	13/11/2019	Draft
LP140100813	Prof Robert Sang ; Prof Damien Hicks ; A/Prof Igor Litvinyuk ; Dr Luke Uribarri	Griffith University	Bright x-ray beams from laser-driven microplasmas	$240,000	10/11/2016	17/11/2018	Draft
LP160101616	Prof Warwick Bowen ; Dr Christopher Baker ; Dr Rachpon Kalra ; Dr Luke Uribarri	The University of Queensland	Scalable nanomechanical information processing	$334,710	20/11/2020	30/06/2021	Draft

D11. Eligibility - Role of Partner Investigator

(Please indicate which of the Partner Investigator role options from A6.3.3 of the Funding Rules apply to your role on this Project. Select all options that apply.)

Have demonstrated the relevant skills and experience to effectively manage a similar scale research Project.

D12. Eligibility - Will you be residing predominantly in Australia for the Project Activity Period?

(This is a 'Yes' or 'No' question. Indicate whether you will be residing predominantly in Australia for the Project Activity Period. If you are applying as a CI and you answer 'No' to this question you will be prompted to contact your Research Office to check your eligibility. If you are a Foreign National, you must reside legally in Australia. Eligibility will be based solely on the information contained in this Proposal.)

No

D13. Eligibility - Are you currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date?

(This is a 'Yes' or 'No' question. If you are applying as a CI and your answer is 'Yes' to this question you will be

prompted to contact your Research Office. Eligibility will be based solely on the information contained in this Proposal.)

No

D14. Eligibility - Employment Details as at Funding Commencement Date of Project

(This question will be used to determine your eligibility. Your eligibility will be based solely on the information contained in this Proposal. Confirm your employment status at all organisations that you will be associated with as at the Funding Commencement Date. Enter the relevant appointment type and Full-Time Equivalent (FTE) for each organisation.)

Org name	Is this an Eligible Organisation?	Please choose your appointment type for this organisation.	Please enter your FTE for this Organisation
Lockheed Martin Corporation		Employee	1.0

D15. Eligibility - Further Details Regarding Partner Investigator Status - Do you hold a remunerated appointment at an Eligible Organisation?

(At A2 Partner Investigator has been selected as the role type, but it appears that the participant meets the criteria of a Chief Investigator.
NOTE: this question is mandatory ONLY FOR PIs WHO:
• at D12 confirmed that they will reside predominantly in Australia for the Project Activity Period of the proposed Project; AND
• at D13 confirmed that they are not currently undertaking a Higher Degree by Research which will be conferred after the Funding Commencement Date; AND
• at D14 indicated that they would hold either:
- an appointment at an Eligible Organisation equal or greater than 0.2 FTE; OR
- an emeritus appointment at an Eligible Organisation

This is a 'Yes' or 'No' question. If you select 'Yes', you will be further prompted to justify your participation on this Proposal as a PI with reference to sections A6.2 and A6.3 of the Funding Rules.)
Do you hold a remunerated appointment at an Eligible Organisation?

Justification of PI status

D16. Eligibility - Relevant Organisation for this Proposal

(Enter the Organisation that is relevant to your participation on this Proposal, and that you will be associated with as at the Funding Commencement Date. The 'relevant organisation' is the primary organisation that will be supporting your involvement in this Project if it is funded. Note that the Organisation must be listed in D14 for this question to validate.)

Relevant Organisation

Lockheed Martin Corporation

D17. What is your time commitment to this Project?

(Enter your time commitment to this Project as a Full-Time Equivalent (FTE). Note that a FTE of 1.0 represents a full-time commitment (i.e. 5 days per week).)

0.05

Part E - Project Cost (LP180100096)

E1. What is the proposed budget for your Project?

(There are rules around what funds you can request from the ARC. You must adhere to the scheme specific requirements listed in the Funding Rules. Refer to the Instructions to Applicants for detailed instructions on how to fill out the Budget section.)

Total requested budget: $595,613

Year 1

Description	ARC	Admin Org		Partner Org		Other Org	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Total	298,936	27,082	246,118	241,266	60,000		19,354
Personnel	225,910	27,082	226,118	27,082	50,000		19,354
Experimental Research Fellow 1.0FTE, RF2.1-2.2 (inc 30% on costs)	118,431						
Theory Research Fellow 1.0 FTE RF 1.4-1.5 (inc 30% on costs)	107,479						
CI Streed 0.5 FTE (inc 30% on costs)			88,277				
CI Carvalho 0.4 FTE (inc 30% on costs)			68,617				
PI Uribarri 0.05 FTE (inc 30% on costs)					15,000		
Theory student				27,082			
Experimental student		27,082					
PI Barnett UK Professor 0.1 FTE (inc 30% on costs)							19,354
PO - Ned Allen, Chief Scientist 0.05 FTE (inc 30% on costs)					25,000		
PO - Technical Assistant 0.05 FTE (inc 30% on costs)					10,000		
CI Vaccaro 0.3 FTE (inc 30% on costs)			69,224				
Teaching Relief				99,116			
Prof J Vaccaro, 0.2 FTE				46,149			
Dr E Streed, 0.3 FTE				52,967			
Equipment	51,276		20,000	96,818			
Theory Computers	10,264						
Laser Wavemeter & 8 Channel Frequency Stabilisation				96,818			
Ion Addressing AOMs	9,725						
Quantum Thermo Ion Trap	31,287		20,000				
Maintenance	6,750			8,250			
Laboratory consumables	1,500						
Misc. Optics	5,250						
Misc. Electronics				3,250			
Misc. Opto-Mechanics				5,000			

Travel	15,000			10,000	10,000		
1 Intl Trip for each CI and RF (5x) @ $5k/ea	15,000			10,000			
Travel for Lockheed Martin Personnel					10,000		

Year 2

Description	ARC	Admin Org		Partner Org		Other Org	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Total	296,677	27,082	226,118	241,267	60,000		19,354
Personnel	233,762	27,082	226,118	27,082	50,000		19,354
Experimental Research Fellow 1.0FTE, RF2.1-2.2 (inc 30% on costs)	122,333						
Theory Research Fellow 1.0 FTE RF 1.4-1.5 (inc 30% on costs)	111,429						
CI Streed 0.5 FTE (inc 30% on costs)			88,277				
CI Carvalho 0.4 FTE (inc 30% on costs)			68,617				
PI Uribarri 0.05 FTE (inc 30% on costs)					15,000		
Theory student				27,082			
Experimental student		27,082					
PI Barnett UK Professor 0.1 FTE (inc 30% on costs)							19,354
PO - Ned Allen, Chief Scientist 0.05 FTE (inc 30% on costs)					25,000		
PO - Technical Assistant 0.05 FTE (inc 30% on costs)					10,000		
CI Vaccaro 0.3 FTE (inc 30% on costs)			69,224				
Teaching Relief				99,116			
Prof J Vaccaro, 0.2 FTE				46,149			
Dr E Streed, 0.3 FTE				52,967			
Equipment	41,165			96,819			
D_5/2 Shelving Laser 411 nm				78,063			
D_5/2 Repump/Raman Laser 976 nm	18,756			18,756			
Optical Table	22,409						
Maintenance	6,750			8,250			
Laboratory consumables	1,500						
Misc. Optics	5,250						
Misc. Electronics				3,250			
Misc. Opto-Mechanics				5,000			
Travel	15,000			10,000	10,000		
1 Intl Trip for each CI and RF (5x) @ $5k/ea	15,000			10,000			
Travel for Lockheed Martin Personnel					10,000		

Partner Organisation

Organisation	Year 1		Year 2	
	Cash	In-kind	Cash	In-kind
Lockheed Martin Corporation	241,266	60,000	241,267	60,000
Total	241,266	60,000	241,267	60,000
Committed Total	241,266	60,000	241,267	60,000

Other Organisation

Organisation	Year 1		Year 2	
	Cash	In-kind	Cash	In-kind
University of Glasgow, UK		19,354		19,354
Total		19,354		19,354
Committed Total		19,354		19,354

Part F - Budget Justification (LP180100096)

F1. Justification of funding requested from the ARC

(Upload a PDF of no more than four A4 pages and within the required format. Fully justify, in terms of need and cost, each budget item requested from the ARC. Use the same headings as in the Description column in the budget at the Project Cost Part of this Proposal.)

Uploaded PDF file follows on next page.

F1 – Justification of funding requested from the ARC

PERSONNEL

Experimental Research Fellow 1.0 FTE RF2.1-2.2 + 30% on costs **$240,764 Cash**

The Experimental Research Fellow (ERF) is in charge of the day-to-day in lab operations under the supervision of CI Streed. The ERF is specifically responsible for the Ion Trap construction (2018) and the 411 nm laser system (2019) under the guidance of CI Streed and with the assistance of the Experimental student. The ERF will be the lead author on significant results reported in high-impact journal papers. The total cost of hiring the ERF over the 2 year duration of the project is **$240,764**, which will be provided by the ARC.

Theory Research Fellow 1.0 FTE RF1.4-1.5 + 30% on costs **$218,908 Cash**

Aim 2 of this proposal involves the development of new theoretical ideas as well as the precise modeling of experiments. Given the breadth of theoretical research in the proposal and the limited time available from the CIs, the amount of work involved to achieve our goals in a timely manner will require the support of a RF with knowledge to transit smoothly between theory and experiments and with high-level computational skills. Accordingly, we plan to hire a Research Fellow at Level 1.4 to carry out this work for a total cost (including on-costs) of **$218,908** over 2 years, which will be provided by the ARC.

EQUIPMENT

Theory Computers **$10,264 Cash**

The project will require extensive computer modeling, with simulations of quantum control protocols and optimisation algorithms. The long and most resource intensive simulations will be run in the high performance computing cluster at Griffith University. However, high-end computing equipment is still required for processing and also visualisation purposes. The budget includes a top-end eight-core iMac pro with 32Mb of memory and 1Tb storage, which runs the preferred software packages. The estimated cost of this equipment is $6709.

Griffith University maintains MATLAB site licenses which will provide, together with free Python and C compilers, as well as Qutip and XMDS packages, the main tools for the numerical modeling. However, it will be essential for the success of the project for the Research Fellow, PhD student and CIs to have licenses for Wolfram Mathematica ($1185 x3) for symbolic processing.

$D_{5/2}$ Repump/Raman Laser 976 nm **$18,756 Cash**

Required for **Task 1.4** to demonstrate entropy concentration experiments in the $D_{5/2}$ state and to state- selectively transfer the $D_{5/2}$ into the readout transitions (cycling $S_{1/2} - P_{1/2}$ on 370 nm and repump $D_{3/2}$ to $[3/2]_{1/2}$) through an incoherent path for **Task 1.3**. Stabilised by the **Laser Wavemeter & 8 Channel Frequency Stabilisation** and will reside on the **Optical Table** for space reasons. The total cost for the system is **$37,512**. Half of this will be provided by the ARC and the other half by LMC.

Ion Addressing AOMs **$9,725 Cash**

Required for **Task 1.2** in order to address individual ions for a demonstrate multiple ion entropy extraction. Fast steering of laser beams using Acousto-optical modulators as deflectors. Includes two AOMs (AA Inc, Isomet, Or Intraction), two RF amplifiers (AA, Pasternack, Mini-Circuits), supporting electronics, and a phase stable dual channel RF frequency source (Rigol, Agilent, Tektronix, or Liquid Instruments) to provide high relative phase stability seed signals to drive Raman transitions. Will initially be installed on the Integrated Diffractive Mirror Chip Trap and then transfered to the **Quantum Thermo Ion Trap**. Observed Ion Addressing system performance (response time, cross-talk, slew effects, etc.) will inform the design of the **Quantum Thermo Ion Trap**.

Optical Table **$22,409 Cash**

Trapped ion experiments and frequency stabilised lasers require a dust free environment with low mechanical vibrations. Our 3 existing Optical Tables are fully occupied. Consists of a honeycomb optical table with active pneumatical damping on four legs sourced from Thorlabs, Newport, or TMC Corp., enclosing canopy/overhead equipment rack, and HEPA air filter. Will hold $\mathbf{D_{5/2}}$ **Shelving Laser 411 nm**, $\mathbf{D_{5/2}}$ **Repump/ Raman Laser 976 nm**, and the **Quantum Thermo Ion Trap**. Very literally supports the hardware required for **Tasks 1.3–1.5**.

Quantum Thermo Ion Trap **$31,287 Cash**

Purpose built ion trapping system designed specifically for Quantum Thermodynamics experiments. Design and construction will be informed by present and projected experiments using existing Integrated Diffractive Mirror Chip Trap, which may be heating rate and laser power limited. Will include larger electrode spacing for lower heating rates, large aperture access for both laser addressing beams and readout optics, compatibility with high power laser beams, and a photon extraction cavity. The latter is necessary to directly observe the increase in coherent photon energy provided by the engine. Costs include vacuum chamber (Kimball Physics), ion gauge (Duniway), vacuum windows and cavity mirrors with custom optical coatings, electrical feedthroughs, in-vacuum fixtures, helical resonator and RF source/amp. Construction will be substantially assisted by available stocks of ion pumps, TiSub pumps, misc. ion trap components, and associated optics/electronics (estimated ~$20k, listed as in-kind). Required for **Task 1.5** as current trapping systems cannot be adapted to work with a photon extraction cavity.

MAINTENANCE

Laboratory consumables **$3000 Cash**

Includes gas bottle rental ($200/yr/each), adhesives, vacuum and optical cleaning solvents, lens cleaning tissue, fasteners (literally nuts and bolts, washers, etc.), tape, Kim-wipes. Vendors include BOC Gases, Sigma-Aldrich, Thorlabs, Blackwoods, and Bunnings.

Miscellaneous Optics **$10,500 Cash**

Optics for linking components of laser systems and interfacing laser systems to the trap. Per piece costs $50-$300. Includes mirrors for routing laser beams and imaging optics, lenses for beam shaping, waveplates and polarising beamsplitters for polarisation control. Optics exposed to ultraviolet light have a finite lifespan due to intensity and dose dependent radiation induced aging processes. Vendors include Thorlabs, Newport, Casix, and Edmund Optics.

TRAVEL

International travel **$30,000 Cash**

This project is a collaborative venture that combines the talents and expertise of its Investigators from three Organisations in three countries. It is imperative for the success of the project that the Investigators meet in person at least annually to coordinate the research. Also, in order to fulfill the plans for dissemination, it is important that results of the research are publicised at International Conferences and Workshops. To economise on cost this is best done by coordinating attendance at international conferences with the PIs.

Approximate cost breakdown: International economy return airfare ($2000), ground transportation ($200, 4 taxis), conference registration fees ($700), accommodation and meals ($1500=7 days x $215/day) amounts to $5k per trip. Example: DAMOP 2019 in Milwaukee, Wisconsin USA ($1850 air, $200 ground, registration US$500, hotel US$191/night x7, meals US$50/day x 7) costs to $4923.

On this budget With in-kind accommodation in the UK Vaccaro is likely able to travel twice a year to Glasgow to visit CI Barnett based on a cost of return airfare ($1750), ground transport

($100), and meals (GBP 25/day x 14 days). An international trip per year for each of 3 CIs and 2 RFs @ $5k totals $50k over the 2 year duration of the project. Travel for international conferences occurring within Australia/New Zealand including CLEO-PR 2020 in Sydney or ICOLS 2019 in Queenstown, NZ may allow for approximately two conferences in a year given reduced airfare costs with supplemental funding and/or reduced accommodation expenses.

We are requesting $15,000/yr for 2 years giving a total of **$30,000** or 60% of the travel budget from the ARC. LMC will provide the 40% balance of $20,000 to cover the remaining travel budget. These amounts will likely be supplemented by various Griffith programs to support ECR conference attendance for the two RFs.

F2. Details of Partner Organisation and other non-ARC contributions

(Upload a PDF of no more than two A4 pages and within the required format, provide an explanation of how non-ARC contributions will support the proposed Project. Use the same headings as in the Description column in the Project Cost Part of this Proposal.)

Uploaded PDF file follows on next page.

F2 – Justification of Partner Organisation and other non-ARC contributions

ADMINISTERING ORGANISATION

PERSONNEL Experimental RHD student 1.0 FTE **$54,164 Cash**

The Experimental Student (ES) will be responsible for the assembly of the **Ion Addressing AOMs** (2018) and the $\mathbf{D_{5/2}}$ **Repump/Raman Laser 976 nm** (2019) under the supervision of CI Streed and the Experimental Research Fellow (ERF). They will assist the ERF and CI Streed in the assembly of the $\mathbf{D_{5/2}}$ **Shelving Laser 411 nm** and the **Quantum Thermodynamics Ion Trap**.

CI Erik Streed 0.5 FTE **$176,554 in-kind**

Dr. Streed is the lead CI and the Experimental Group Leader, supervising the experimental research activities, mentorship of the Research Fellow and RHD students involved, higher level interpretation of experimental results, design work, and strategic assessment of the supporting technologies.

CI Andre Carvalho 0.4 FTE **$137,234 In-kind**

Dr. Carvalho is the Theoretical Group Leader. This entails overall supervision of the theoretical activities, including managing, planning, execution, and mentoring the theory RF and HDR students. This is a high level of commitment that will be covered by a contribution of 0.4FTE (equivalent to $66,793 per year in-kind) from his current research only contract.

CI Joan Vaccaro 0.3 FTE **$138,448 in-kind**

CI Vaccaro will play a leading role in conceptual issues of the project. Her previous partnership with LMC in Linkage Project LP140100797 and her experience in the field puts her in a prime position to mentor CI Streed and CI Carvalho throughout this project.

EQUIPMENT

Quantum Thermo Ion Trap **$20,000 In-Kind**

Split funding with ARC. Represents existing components. See description in F1.

PARTNER ORGANISATION: Lockheed Martin Corporation (LMC)

PERSONNEL

Theory RHD student 1.0 FTE **$54,164 Cash**

The modelling of ion traps in different configurations planned for Aim 2 is ideal for the developing theoretical and numerical skills of a RHD student in theoretical quantum research.

PI - Luke Uribarri 0.05 FTE **$30,000 In-kind**

Dr Luke Uribarri, Deputy to the Chief Scientist at LMC, will provide intellectual input into both Aims of the project through his knowledge of energy storage systems based on quantum thermodynamics. He is the primary contact at LMC and will coordinate activity with other related experimental and theoretical efforts. He will also provide key advice regarding technology transfer issues which will enhance the long term economic impact of the Project.

PO - Ned Allen, Chief Scientist 0.05 FTE **$50,000 In-kind**

Dr Ned Allen will provide guidance regarding extensions of the core concepts and potential new applications. He will also provide invaluable assistance through the extensive number of contacts he has in his role as Chief Scientist at Lockheed Martin's **Skunk Works** research and development laboratory.

PO - Technical Assistant 0.05 FTE **$20,000 In-Kind**

PO Lockheed Martin will also provide the services of a Technical Assistant at 0.05 FTE to assist with protection of intellectual property generated by the Project.

TEACHING RELIEF

Dr E Streed, 0.3 FTE **$105,934.00 Cash**

To increase the amount of time committed to this project from 0.2 to 0.5 FTE LMC is providing a cash contribution to allow CI Streed's to focus increased attention on the technical details of this project where his previous experimental expertise will have a large benefit.

Prof J Vaccaro, 0.2 FTE **$92,298 Cash**

LMC will continue to support CI Vaccaro's work in Quantum Thermodynamics, increasing her commitment to this project from 0.1 to 0.3 FTE overall. This level of commitment is necessary in order for her to guide the theoretical research component of the project, mentor the other CIs and help supervise the RF and RHD student.

EQUIPMENT

Laser Wavemeter & 8 Channel Frequency Stabilisation **$96,818 Cash**

Trapped ion quantum physics experiments require high accuracy absolute frequency stablisation of the laser outputs to better than 10^{-8}. We will replace our numerous high cost, high maintenance legacy frequency stabilisation systems (@λ =369.5, 399, 638, & 935 nm) with this solution which is now standard in other ion trapping labs. Supports the **Quantum Thermo Ion Trap** as well as $\mathbf{D_{5/2}}$ **Shelving Laser 411 nm** and $\mathbf{D_{5/2}}$ **Repump/Raman Laser 976 nm**. Support for hardware required in **Tasks 1.1–1.5**.

$\mathbf{D_{5/2}}$ Shelving Laser 411 nm **$78,063 Cash**

Required for **Task 1.3** to demonstrate the proposed Expansion Step by implementing the classic Cirac-Zoller gate and for Entropy concentration **Task 1.4** within the $D_{5/2}$ state. Constructed from a commercial laser system combined with locking to a narrow-linewidth low-drift reference cavity. Requires $\mathbf{D_{5/2}}$ **Repump/Raman Laser 976 nm** for efficient state selective readout. The very narrow linewidth (23Hz) requires a separate **Optical Table** for vibration isolation. Pre-stablised using the **Laser Wavemeter & 8 Channel Frequency Stabilisation**.

$\mathbf{D_{5/2}}$ Repump/Raman Laser 976 nm **$18,756 Cash**

50/50 split funding. See description in F1. The total cost for the system is **$37,512**.

MAINTENANCE **$16,500 Cash**

Miscellaneous Electronics **$6,500 Cash**

Includes power supplies, oscilloscopes & signal generators, digital voltmeters, cables and connectors, and enclosures for minor custom electronics devices.

Miscellaneous Opto-Mechanics **$10,000 Cash**

Low vibration, low thermal drift mechanical systems for holding and adjusting mirrors and lenses. Price per component is $100-$500 for manual units and >$1000 for computer control.

TRAVEL

International travel **$20,000 Cash**

Split funding See description in F1.

Travel for Lockheed Martin Personnel **$20,000 In-Kind**

Teams from LMCO visit Australia at least twice a year for face-to-face meetings to coordinate research, communicate results, and contribute their insights to the project.

OTHER ORGANISATION: University of Glasgow

PERSONNEL

PI - Stephen Barnett UK Professor 0.1 FTE **$38,708 In-Kind**

Prof. Barnett is a key member of the theoretical team. He is co-author (with CI Vaccaro) of the ground-breaking papers (Refs. [4-6] in C1 Project) on the erasure of information without an energy cost which is central to this project. He will provide his expert and broad knowledge in theoretical physics to **Tasks 2.2 and 2.3**.

F3. Does this Proposal request funding for research activities, infrastructure or a Project previously funded, or currently being funded, with Commonwealth funds (from the ARC or elsewhere)?

(This is a 'Yes' or 'No' question.)

No

Funded Project ID

The Administering Organisation must upload a letter of no more than two pages outlining the similarities and explaining how these similarities will be managed if this Proposal is funded.

No PDF file uploaded.

F4. Does this Proposal request funding for research activities or infrastructure which are the subject of a proposal already submitted to the ARC?

(This is a 'Yes' or 'No' question.)

No

If yes, provide the Proposal ID

The Administering Organisation must upload a letter of no more than two pages outlining the similarities and explaining why more than one Proposal has been submitted for the same research.

No PDF file uploaded.

Part G - Research Support and Statements on Progress (LP180100096)

G1. Research support for all participants

(For each participant on this Proposal, provide details of:
i) current submitted ARC Proposals (i.e. for which the outcome has not yet been announced);
ii) any newly funded ARC Projects which are not yet showing in the participant's question (Currently held ARC Projects); and
iii) research funding from non-ARC sources (in Australia and overseas). For research funding from non-ARC sources, list all projects/proposals/awards/fellowships awarded or requests submitted involving that participant for funding for the years 2017 to 2023 inclusive.)

Uploaded PDF file follows on next page.

Part G1 - Research Support from all participants

Current ARC Proposals and newly funded ARC Projects which are not yet active

Description (All named investigators on any proposal or grant/fellowship in which a participant is involved, project title, scheme and round)	**Same Research Area** (Yes/No)	**Support Status** (Requested/Current/Past)	**Proposal/ Project ID**	**2017** ($'000)	**2018** ($'000)	**2019** ($'000)	**2020** ($'000)	**2021** ($'000)	**2022** ($'000)	**2023** ($'000)
E.W. Streed, A.R.R.Carvalho, J.A.Vaccaro, S.M.Barnett, L.Uribarri, "*An Engine Powered by Memory*", ARC, Linkage 2018	Yes	R	LP180100096		245	275				

Funding from non-ARC sources

Description (All named investigators on any proposal or grant/fellowship in which a participant is involved, project title, source of support, scheme and round)	**Same Research Area** (Yes/No)	**Support Status** (Requested/Current/Past)	**Proposal/ Project ID** (for NHMRC proposals only)	**2017** ($'000)	**2018** ($'000)	**2019** ($'000)	**2020** ($'000)	**2021** ($'000)	**2022** ($'000)	**2023** ($'000)
J.A.Vaccaro, *"Coherence capacitor"*, Lockheed Martin Corporation, Commercial research consultancy	Yes	P	n/a	198						

E.W. Streed and M. Lobino "*Quantum Device Photonic Interconnects*", US Army Research, Development, & Engineering Command International Technology Centre-Pacific, 2017	No	C	n/a		48					
E.W. Streed and M. Lobino "*A telecom fibre linked Quantum Repeater Node with trapped ions*", Australian Department of Defense Science & Technology, Next Generation Technologies Fund/Quantum Technologies Research Network, 2018	No	R	n/a		126	315	278	153		
S.M.Barnett, *"Royal Society Research Professorship"*, Royal Society UK, Royal Society Research Professorships	No	C	n/a	332	332	332	332	249		
S.M.Barnett, *"Foundations and Applications of Optical Forces,"* Royal Society UK, Research Professorships Enhancement Award	No	C	n/a	19	226	226	207			
S.M.Barnett, "*Relativistic Electron Vortices*," EPSRC UK, Responsive mode grant	No	C	n/a	25	152	152	127			

G2. Statements on Progress for ARC-funded Projects

(A progress statement must be provided for any currently funded ARC Project that involves a participant on this Proposal. This requirement applies to all ARC funding with the exception of ARC Centres of Excellence, Supporting Responses to Commonwealth Science Council Priorities, Learned Academies Special Projects and Special Research Initiatives schemes. Refer to the Instructions to Applicants for further information.)

Project ID

LP140100797

First Named Investigator

Prof Joan Vaccaro

Scheme

Linkage Projects

Statement

Uploaded PDF file follows on next page.

G2. Statement on Progress for ARC-funded Project LP140100797 2014-2018

The goal of the project is to exploit the new possibilities afforded by the Vaccaro-Barnett erasure mechanism in the development of a new energy technology. Instead of a minimum energy cost associated with the erasure of information in accord with Landauer's erasure principle, the new mechanism erases information at the cost of depleting the spin polarisation of a collection of spins instead of energy. The specific aims of the project are:

1 to explore quantum dot heat engines operating on the new erasure mechanism, and

2 to develop the supporting thermodynamical framework.

The reason for choosing quantum dots as a basis for demonstrating a new kind of heat engine design in aim **1** is that semiconductor heterostructures are a well-developed technology with demonstrated potential for being scaled up for practical implementations in line with the long term goal of PO Lockheed Martin Corporation. We have now successfully designed and modelled a heat engine using quantum dot technology [3]. One of the outcomes of this work was the realisation that, due to a requirement of extremely large magnetic field gradient, the quantum dot heat engine design would be extremely difficult to implement with current technology. As a result, attention was subsequently turned to the proposal of a similarly designed heat engine using ion trap technology with the intention that, with an appropriate amount of additional funding, experimentalist Dr Erik Streed would be able to implement in his ion trap lab at Griffith University. We have now designed and modelled an ion trap heat engine [5].

In regards to aim **2**, we have developed the theory describing the statistics of the fluctuations in the cost of the new erasure mechanism [1]. This work is important for assessing the performance of heat engines averaged over many cycles of operation. We extended the possibility of information erasure to the case where the cost is lost coherence (i.e. reduction in the off diagonal terms of the density matrix in the energy basis) instead of depleted spin polarisation or energy dissipation. In support of this result, we clarified the situation regarding the ability of coherence to be catalytic and showed that coherence is inevitably consumed when it is used [2]. We have reviewed our results for a book chapter on quantum thermodynamics [4]. Finally, we have explored the extent to information erasure is affected by systems that are described by non-extensive statistical mechanics [6].

Publication outputs to date

[1] T. Croucher, S. Bedkihal and **J.A. Vaccaro**, **PRL**
"Discrete Fluctuations in Memory Erasure without Energy Cost", *Physical Review Letters* 118, 060602 (2017).

[2] **J.A. Vaccaro**, S. Croke and **S.M. Barnett**,
"Is coherence catalytic?", *Journal of Physics A*, in press (2018). https://arxiv.org/abs/1804.05154

[3] J.S.S.T. Wright, T. Gould, **A.R.R. Carvalho**, S. Bedkihal, **J.A. Vaccaro**
"Quantum heat engine operating between thermal and spin reservoirs", *Physical Review A* **97**, 052104 (2018).

Publication outputs accepted for publication

[4] T. Croucher, J. Wright, **A.R.R. Carvalho**, **S.M. Barnett** and **J.A. Vaccaro**, **Invited**
"Information Erasure", invited chapter for F. Binder, L. Correa, C. Gogolin, J. Anders, G. Adesso (Editors) *Thermodynamics in the quantum regime - Recent progress and outlook* (Springer, 2018) currently under peer review. https://arxiv.org/abs/1803.08619

Publication outputs in progress

[5] **A.R.R. Carvalho**, **E. Streed** and **J.A. Vaccaro**, Proposal for an ion-trap heat engine converting spin into work, in progress (2018).

[6] T. Gould, E. Cavalcanti, **J.A. Vaccaro**, Landauer erasure in non-extensive statistical mechanics, in progress (2018).

Project ID

LP140100595

First Named Investigator

Prof Warwick Bowen

Scheme

Linkage Projects

Statement

Uploaded PDF file follows on next page.

Statement on Progress: LP140100595

First named investigator: Prof. Warwick Bowen

Scheme: ARC Linkage

Project Title: Optomechanical refrigeration of electronic circuits

This project seeks to apply optomechanical cooling techniques to improve the performance of electronic devices in conjunction with Lockheed Martin. Optical fields can be generated with relative ease with noise performance at the quantum limit (or shot noise limit). By comparison, due to the much lower characteristic frequencies involved in radio and microwave frequency circuits, their performance is constrained by thermal (or Johnson-Nyquist) noise. Cavity optomechanical systems provide a method to strongly couple a mechanical degree-of-freedom to both an optical and electrical fields. This allows some of the beneficial features of light to be translated into the electrical domain. The project is developing on-chip clocks, oscillators, and receivers with the aim of out-performing purely electrical analogues in precision, noise performance and robustness.

Our primary results to-date are the development of the first integrated ultrahigh quality cavity optomechanical system [1], and the use of this system to demonstrate a radiation pressure driven on-chip clock [2]. This system integrates capacitive actuation onto microscale ultrahigh quality whispering gallery mode resonators. Technologically, it advances fabrication techniques demonstrating for the first time that metallic structures can be fabricated on such devices without loss of quality. It, further, allows tuning of the optical resonances of the devices with bandwidth several orders of magnitude greater than has previously been possible, and requiring exceptionally low energy consumption. This is an important capability for applications of whispering gallery mode resonators in on-chip lasing, photonic circuits, and communications. We have patented this work [3,4]. We have, further, designed new architectures for whispering gallery mode cavity opto-electromechanics that – according to predictions – will greatly increase both the optical and electrical coupling to the mechanical element, allowing full free-spectral range tuning for silica microcavities on a silicon chip for the first time; fabricated the high quality double disk structures that are the key building block for these architectures; and fabricated and tested phononic waveguides for the controlled propagation of acoustic waves on chip.

Our work from this project has been reported in both international and domestic conferences.

[1] C. G. Baker, C. Bekker, D. L. McAuslan, E. Sheridan and W. P. Bowen, *High bandwidth on-chip capacitive tuning of microtoroid resonators*, Optics Express **24** 20400–20412 (2016).

[2] C. Bekker and W. P. Bowen. *Injection locking of an electro-optomechanical device*. Optica **4** 1196 (2017).

[3] C. Baker and W. P. Bowen. *Low energy tuning of on-chip optical resonators*. Australian Provisional Patent Application, PAT-02223-AU-01 (2015).

[4] C. Baker and W. P. Bowen. *Tunable optical device*. International Patent Application, PAT-02223-WO-01 (2016).

Project ID

LP140100813

First Named Investigator

Prof Robert Sang

Scheme

Linkage Projects

Statement

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Bright x-ray beams from laser-driven microplasmas (LP140100813)

Though the project was expected to be completed in two years, the challenges associated with the number density of the plasma and unavailability of project fund to buy another nanosecond laser (though this was our original plasma) in order to improve the number density limited us to step back from the original aim of the experiment. Also problems associated delay between plasma generating and HHG driving pulse (delay is now being introduced with the help of physical optical path by compromising the energy of HHG driving pulse) challenged the execution of the project to its fullest due to unavailability of independent lasers as mentioned in the project description. Further, frequent shut down of the laser, which is the main component of our experiment, delayed the project by about 6 to 7 months. With all difficulties and challenges, we have managed to set up a fully operating laser produced plasma system and HHG experimental setup based on LPP. The characterization of HHG from plasma is still a concern due to the above mentioned problems and it can be concluded after the final test regarding the HHG by a Ph.D student working on the project now. The following are the outcomes of the project at the time of writing:

Constructed a new experimental set up for the generation of laser produced plasma (LPP).
Acquired a new Intensified CCD (ICCD) and spectrometer by the beginning of 2016 from Princeton Instruments, which is now a part of the LPP set up.
The waiting period for delivery of the new ICCD and spectrometer was utilised to establish a collaboration with Prof. Reji Philip at the Raman Research Institute, Bangalore, India, where optical emission spectroscopy (OES) of picosecond (ps) and nanosecond (ns) laser produced chromium and aluminium plasmas were carried out successfully. A paper titled “Spatio-temporal optimization of a laser produced Al-plasma: Generation of highly ionized species” on the optimization of a laser generated micro-plasmas towards the generation of harmonics has been published in the *Physics of Plasmas* **23**(11), 113104(2016).
Time-integrated measurement of chromium plasma was also carried out and the results are now written in the form of a manuscript and is ready for communication.
From the initial LPP measurements, it was noticed that the number density of plasma is orders of magnitude less than what we aim at.
A double pulse plasma generation method is expected to give better results with regards to the magnitude of number density
A spatio-temporal characterization of aluminium LPPs generated in single pulse and double pulse scheme was carried out using optical emission spectroscopy and time-resolved imaging method and the important results is communicated for publication.
A complete spatio-temporal investigation of a laser produced chromium plasma was carried out using optical emission spectroscopy and fast imaging using ICCD. The data is being analysed and a new manuscript is being prepared which would be ready for communication soon.
XUV detection part was designed and integrated to the LPP experimental setup which is ready for further experiments in high-order harmonic generation.
Calibration of XUV detector was necessary as it was a custom made unit and not designed for HHG experiment.
A few modifications were made in the set up so as to detect the harmonics and the detection system has been tested using argon gas jet. Knowing the harmonics generated from argon gas, the XUV spectrometer was calibrated and the system is now ready to go for plasma based HHG measurement with 7 months delay in the project due to an issue associated with the laser.
Initial tests carried out to drive HHG from laser generated plasmas indicate large plasma background reaching the XUV detector, which is a great challenge that has been addressed to detect any harmonics if generated and a Ph.D student is now working on the project to address these challenges.
Further, we also have carried X-ray emission characteristics from 30 keV to 150 keV fro upon irradiating solid m Al, Cr and Al-Cr with 1 mJ, 100 fs pulse using single pulse and double pulse scheme in collaboration with Raman Research Institute, Bangalore, India during 20 Nov- 25 Nov 2017 and we are currently analysing the data.

Project ID

LP160101616

First Named Investigator

Prof Warwick Bowen

Scheme

Linkage Projects

Statement

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Statement on Progress for ARC-funded Project: LP160101616
First named investigator: *Prof Warwick Bowen.*
Scheme: *ARC Linkage Grant*
Project Title: *Scalable nanomechanical information processing*

This project has begun only very recently, with the contract signed by UQ and Lockheed in November 2017 (5 months ago). We have already made progress on several fronts.

- Numerical simulation

In Years 1 and 2 of the project, the various building blocks of a phononic computer will be demonstrated with low frequency (10 MHz-100 MHz) phonons, with wavelengths in the tens of micrometres. The devices will later be miniaturized by operating at GHz frequencies. Figure 1 (a) shows a finite element method simulation of a guided acoustic wave in a MHz phononic waveguide. Proper engineering of the phononic bandgap enables dramatic suppression of energy leakage out of the waveguide, a necessary a condition for the ability to cascade numerous logic gates.

- Fabrication

We have begun fabricating the first generation of devices in the Australian National Fabrication Facility (ANFF) cleanroom. Acoustic vibrations are guided in a single-mode phononic waveguide made from a suspended high-tensile stress silicon nitride membrane over a silicon substrate, see Figs 1 (b) & (c).

- Experimental setup

We are currently building the experimental characterization setup. Small amplitude mechanical motion driven by capacitive actuation is detected through a heterodyne optical detection scheme. Measurements take place inside a custom built vacuum chamber.

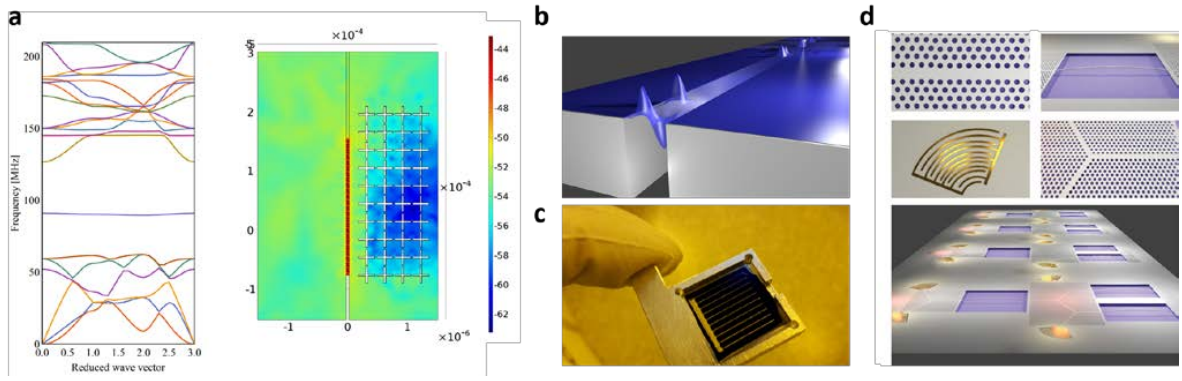

Figure 1. (a) Left: Phononic band structure calculation. Right: the presence of a phononic crystal lattice on the right side of the waveguide greatly reduces the acoustic power loss, compared to the unshielded left side. (b) Artistic rendering of acoustic waves propagating along a single-mode silicon nitride membrane waveguide. (c) Picture of first proof-of-principle chip fabricated in the ANFF cleanroom. (d) Elemental building blocks of a scalable nanomechanical computing architecture, from top to bottom: phononic waveguide; mechanical resonator providing the mechanical non-linearity for logic operations; interdigitated capacitor actuator; phononic y-splitter; cascaded mechanical logic architecture.

Project ID

DP130101613

First Named Investigator

E. W. Streed

Scheme

Discovery Projects

Statement

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G2 Statement on Progress for ARC-funded Project: DP130101613
First named investigator: *Dr. Erik Streed*
Scheme: *ARC Discovery Project*
Project Title: *Building Schrodinger's cat: large-scale entanglement of trapped ions*

This project aimed to perform large-scale entanglement of trapped ions by exploiting ultrafast light-atom interactions, and to experimentally test the theoretical proposals that may radically speed up quantum logic gates.
On the theoretical side, we investigated the scaling [1], stability and performance [2], and the application [3] of the ultrafast entangling gates developed by the ANU group. Our analysis in [1] shows the effect of the number of ions in the chain and the inter-ion distance on the fidelity and speed of the logical gates, while in [2] we investigate the effect of errors and imperfections on our gates. We also applied our fast-gate protocol to the problem of digital quantum simulation [3]. Our work, which proposes a method of implementing a multiqubit gate in shorter time and with more precision than existing alternatives, would enable digital quantum simulations to outperform classical computers without error correction. This work is the result of the solid collaboration established by this Discovery Project as it originated from a combined effort of the theoretical team at the ANU and the group of PI Solano.
The experimental group completed development of the picosecond pulsed UV source and are preparing for the first experiments to deliver resonant optical π pulses to trapped Yb^+ ions. The UV source [4] is a continuation of the work we have already established to create a source with the necessary pulse characteristics [5] for implementing ultrafast coherent gates. We also continued our development of tools for achieving large-scale quantum computing [6-8] and diagnostic tools for measuring the forces associated with the ultrafast coherent gates [9]. The experimental team is presently pursuing realisation of ultrafast coherent strong forces as a precursor to experimentally demonstrating of ultrafast coherent gates.

[1] C.Bentley, A.Carvalho, and J. J. Hope, *New J. Phys.* **17**, 103025 (2015).
[2] C.Bentley, R.Taylor, A.Carvalho, J.J.Hope, *Phys. Rev.* A **93**, 042342 (2016).
[3] R.L.Taylor, C. D. B. Bentley, J. S. Pedernales, L. Lamata, E. Solano, A. R. R. Carvalho, J. J. Hope, submitted to Sci. Reports. (arXiv:1601.00359).
[4] Hussain, M., Petrasiunas, M., Bentley, C. D. B., Taylor, R. L., Carvalho, A. R. R., Hope, J. J., Kielpinski, D., *Optics Express*, **24**(15), 16638–16648 (2016).
[5] M. J. Petrasiunas, M. I. Hussain, J. Canning, M. Stevenson, D. Kielpinski Optics Express **22** (15), 17716-17722 (2016).
[6] D. Kielpinski, C. Volin, E. W. Streed, F. Lenzini, and M. Lobino, Quantum Information Processing, 1–24 (2015)
[7] S Kasture, F Lenzini, B Haylock, A Boes, A Mitchell, EW Streed, M Lobino *J. Opt.* **18** 104007 (2016)
[8] M Ghadimi, V Blūms, BG Norton, PM Fisher, SC Connell, JM Amini, C Volin, H Hayden, C-S Pai, D Kielpinski, M Lobino, EW Streed *npj Quant. Info.* **3** 4 (2017)
[9] V Blūms, M Piotrowski, MI Hussain, BG Norton, SC Connell, S Gensemer, M Lobino, EW Streed *Science Advances* **4** eaao4453 (2018)

Project ID

FT130100472

First Named Investigator

E. W. Streed

Scheme

Future Fellowships

Statement

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G2 Statement on Progress for ARC-funded Project: FT130100472
First named investigator: *Dr. Erik Streed*
Scheme: *ARC Future Fellowship*
Project Title: *Trapped Ion Imaging for Biomolecular Dynamics*

This project aimed to investigate the folding of large biomolecules determines their shape and drives their biochemical properties. To investigate folding processes I endeavored to isolate single biomolecules in an ion trap and alter their structure a few atoms or electrons at a time. This was a high risk/high reward approach into a mostly undeveloped area that would require substantially more technological development than anticipated at the time of the proposal. Established techniques for isolating large biomolecules in a form suitable for ion trapping were found to be substantially more complicated and less adaptable in practice. In addition the project was impeded by an international PhD student who had misrepresented their capabilities and issues with the then nascent nature of the physics laboratory infrastructure on the Gold Coast campus. I'm presently collaborating with fellow Institute for Glycomics member cell biologist Dr. Joe Tiralongo on ion trapping and controlled in trap fragment of yeast cells. This effort has been revamped to make use of available undergraduate talent in the absence of Physics PhD candidates. We have succeeded in reproducibly trapping individual cells with differentially fluorescently labeled organelles and the encompassing cystol. We are presently pursuing work on rigorous particle charaterisation and in-trap Coulomb driven cell fragmentation.

This fellowship has produced 8 C1 research outputs in high impact journals including Streed last author works in Science Advances and nature partner journal Quantum Information. Notable accomplishments of this fellowship are the demonstration of a 3 dimensional sub-attoNewton force detection [8] with an observed sensitivity high enough to measure the dipole of moment of a single trapped biomolecule such as insulin. The force used a super-resolution imaging technique that achieved nm level resolution in substantially sub-optimal trapping conditions, which is highly encouraging for the development of future imaging based sensing both in emissions directly from fluorescently labeled biomolecules as well as electric field distribution measurements inferred from co-trapped atomic coolant ions. The result [8] achieved Nature, Science Daily, and PhysOrg.com

Spectroscopic techniques from this project were adapted to multi-disciplinary work in geochronology [3] and materials science [4].

[1] D. Kielpinski, C. Volin, E. W. Streed, F. Lenzini, and M. Lobino, *Quant. Info. Proc.*, 1–24 (2015)
[2] B Haylock, F Lenzini, S Kasture, P Fisher, EW Streed , M Lobino *Rev. Sci. Instr.* **87** 054709 (2016)
[3] DK Borombovits, EW Streed , TJ Pietsch, JM Olley *Rad. Meas.* **95** 1-8 (2016)
[4] AR Md Foisal, A Qamar, H-P Phan, T Dinh, K-N Tuan, P Tanner, EW Streed, DV Dao ACS Appl. Mat. Inter. **9** 3992139925 (2017)
[5] Z Wan, EW Streed , M Lobino, S Wang, RT Sang, IS Cole, DV Thiel, Q Li *Adv. Mat. Tech.* Online Preview Art. 1700315 (2018)
[6] S Kasture, F Lenzini, B Haylock, A Boes, A Mitchell, EW Streed, M Lobino *J. Opt.* **18** 104007 (2016)
[7] M Ghadimi, V Blūms, BG Norton, PM Fisher, SC Connell, JM Amini, C Volin, H Hayden, C-S Pai, D Kielpinski, M Lobino, EW Streed *npj Quant. Info.* **3** 4 (2017)
[8] V Blūms, M Piotrowski, MI Hussain, BG Norton, SC Connell, S Gensemer, M Lobino, EW Streed *Science Advances* **4** eaao4453 (2018)

Part H - Partner Organisation Details (Lockheed Martin Corporation)

H1. Is this a Partner Organisation whose funds are appropriated predominantly from Commonwealth or Australian State or Territory funding sources for the purposes of research?

No

H2. Type of Partner Organisation

(Is this Partner Organisation an Exempt Archive and Public Record Office, an Exempt Charity, an Exempt Herbarium, an Exempt Museum and Collecting Organisation, an Exempt Non-Profit Organisation, an Exempt Small Business or an Exempt Start-up? Please refer to Sections D3 and D5.2.6 of the Funding Rules and the Instructions to Applicants for further information.)

No

Type of Exempt Organisation

H3. Attach a letter of support for this Proposal including Partner Organisation certification

(Please attach a PDF of no more than two A4 pages of the Partner Organisation letter of support, signed by the CEO or delegate. Please refer to Section A5.2.4 of the Funding Rules for details of the required content for this letter.)

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Lockheed Martin Corporation
6801 Rockledge Drive, Bethesda, MD 20817
(301) 897-6000

April 09, 2018

Professor Sue Thomas
Chief Executive Officer
Australian Research Council
GPO Box 2702
Canberra ACT 2601
Australia

Dear Professor Thomas,

I am writing to express the full support of Lockheed Martin Corporation as the Partner Organization for Linkage Project LP180100096, "A Memory Powered Engine."

Headquartered in Bethesda, MD, U.S.A., Lockheed Martin is a global security and aerospace company that employs about 116,000 people worldwide and is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services. The company has a significant presence in Australia through Lockheed Martin Australia Pty Ltd, which is headquartered in Canberra, and the Science, Technology, Engineering Leadership and Research Laboratory (STELaR Lab) in Melbourne, which is Lockheed Martin's first multi-disciplinary R&D facility outside of the United States.

Lockheed Martin has an interest in a wide range of advanced materials and processes for energy storage, structures, and functional nanomaterials. The technologies we develop, and the customers we serve, would almost universally benefit from significant advances in energy storage technology, since platforms as diverse as handheld radios, jet aircraft, and space vehicles are all subject to limitations of energy availability. The vision that I and others have pursued in our work to date with Professor Vaccaro and Dr. Streed was of a technology of fantastic impact and but unclear development path. The progress made under the previous Linkage project (LP140100797) has pointed the way forward to a convincing demonstration of the underlying science. We are very pleased with the direction that the work has taken so far, and the proposed research represents an excellent opportunity for Lockheed Martin to support improvements to products across our supply chain.

This project naturally fits Lockheed Martin's desire to establish and maintain strong links to high-tech research underway in Australia. Lockheed Martin seeks to aid in the development of high-tech industries in Australia with the objective of leveraging these industries to enhance the products and services provided by the company. We would be highly supportive of commercialization within Australia of successful outcomes from this Linkage project, because of the quantity of expertise in the field already existing in the country.

If ARC awards Griffith University the Linkage Project referenced above, Lockheed Martin intends to provide the following contributions in 2018, and 2019:

2018: • Cash: AU$241,266 • In-kind: AU$60,000	2019: • Cash: AU$241,266 • In-kind: AU$60,000

The cash contribution will primarily support salary costs at Griffith University. The in-kind contributions include:

- Personnel: Members of the Lockheed Martin Chief Scientist's Office will collaborate with and manage this project, with the intent that Lockheed Martin will become conversant in all possible applications of the technology. The expected contributors from the CSO to this project (and their loadings) include our Chief Scientist (5%), a deputy (5%), and a technical assistant (5%). These time contributions will be dedicated to program management, transfer of technology from research to commercialization, and new applications development. Time and "in kind" costs associated with this effort are estimates and will not be discretely tracked during the actual project
- Other (Travel): It is expected that the requirements of management and technology transfer for this project will entail visits to Griffith University by the Lockheed Martin project staff, at a level of at least two visits per year to maintain project momentum.

Lockheed Martin's cash support to this project at Griffith University is provisioned from Independent Research and Development (IRAD) funding. Lockheed Martin accounts for IRAD costs as part of the general and administrative costs that are allocated among all of our contracts and programs in progress under U.S. Government contractual arrangements and charged to cost of sales.

Lockheed Martin's support is conditioned on the execution of an agreement with Griffith University containing mutually acceptable terms and conditions including, but not limited to, intellectual property rights, representations and warranties. In accordance with the ARC's requirements, I certify that no part of the cash contribution is drawn from funds previously appropriated or awarded from Commonwealth or Australian State or Territory sources for the purposes of research; and I further certify that Lockheed Martin will meet the requirements outlined in a standard Linkage Projects Funding Agreement, including the requirement to enter into arrangements regarding intellectual property.

Yours sincerely,

E. H. "Ned" Allen
Corporate Chief Scientist
Lockheed Martin Corporation

H4. Partner Investigator participating on this Proposal for this Partner Organisation, where applicable

Dr Luke Uribarri

Certification

Certification by the Deputy/Pro Vice-Chancellor (Research) or their delegate or equivalent in the Administering Organisation

I certify that—

- I have read, understood and complied with the *ARC Funding Rules for schemes under the Linkage Program (2017 edition)*, (the Funding Rules) and, to the best of my knowledge all details provided in this Proposal form and in any supporting documentation are true and complete in accordance with the Funding Rules.
- Proper enquiries have been made and I am satisfied that the participants and the organisations listed in this Proposal meet the requirements specified in the Funding Rules.
- I will notify the ARC if there are changes to any named participant or organisation after the submission of this Proposal.
- The listed participants are responsible for the authorship and intellectual content of this Proposal, and have appropriately cited sources and acknowledged significant contributions to this Proposal.
- To the best of my knowledge, all Conflicts of Interest relating to parties involved in or associated with this Proposal have been disclosed to the Administering Organisation, and, if the Proposal is successful, I agree to manage all Conflicts of Interest relating to this Proposal in accordance with the *Australian Code for the Responsible Conduct of Research (2007)*, the *ARC Conflict of Interest and Confidentiality Policy* and any relevant successor documents.
- I have obtained the agreement, attested to by written evidence, of all the relevant persons and organisations necessary to allow the Project to proceed. This written evidence has been retained and will be provided to the ARC if requested.
- This Proposal complies with the eligible research requirements set out in the *ARC Medical Research Policy*, located on the ARC website.
- This Proposal does not request funding for the same research activities, infrastructure or Project previously funded or currently being funded through any other Commonwealth funding.
- If this Proposal is successful, I am prepared to have the Project carried out as set out in this Proposal and agree to abide by the terms and conditions of the Funding Rules and the *ARC Funding Agreement regarding funding for schemes under the Linkage Program (2017 edition)*.
- The Project can be accommodated within the general facilities of this organisation and if applicable, within the facilities of other relevant organisations specified in this Proposal and sufficient working and office space is available for any proposed additional staff.
- All funds for this Project will only be spent for the purpose for which they are provided.
- The Project will not be permitted to commence until appropriate ethical clearance(s) has/have been obtained and all statutory requirements have been met.
- I consent, on behalf of all the parties, to this Proposal being referred to third parties, including to overseas parties, who will remain anonymous, for assessment purposes.
- I consent, on behalf of all the parties, to the ARC copying, modifying and otherwise dealing with information contained in this Proposal.
- To the best of my knowledge, the Privacy Notice appearing at the top of this form has been drawn to the attention of all the participants whose personal details have been provided in the Personnel section.
- To the best of my knowledge, the Partner Organisation(s) involved in this Proposal are solvent at the time of submission of this Proposal.