AUSTRALIAN RESEARCH COUNCIL
Linkage - Projects
Proposal for Funding Commencing in 2014

LP

PROJECT ID: LP140100797

First Investigator: A/Prof Joan Vaccaro

Admin Org: Griffith University

Total number of sheets contained in this Proposal: 84

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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 *Linkage Projects Funding Rules for funding commencing in 2014*, 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 these Funding Rules.
- Proper enquires have been made and I am satisfied that the Participants and the organisations listed in this Proposal meet the requirements specified in the ARC *Linkage Projects Funding Rules for funding commencing in 2014*. I will notify the ARC if there are changes to any named Participant or organisation after the submission of 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 this 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).
- I have obtained the agreement, attested to by written evidence, of all the relevant participants 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 is not substantially aimed at understanding or treating a human disease or health condition (as per the ARC definition of Medical and Dental Research located on the ARC website).
- This Proposal does not duplicate Commonwealth-funded research including that undertaken in a Commonwealth-funded Research Centre.
- 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 ARC *Linkage Projects Funding Rules for funding commencing in 2014* and the ARC *Linkage Funding Agreement for funding commencing in 2014*.
- The Project can be accommodated within the general facilities in 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, 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 at the Personnel section.

PART A - Administrative Summary (LP140100797)

A1. If this proposal is successful, which organisation will it be administered by?

Administering Organisation Name

Griffith University

A2. Proposal Title

(Provide a short descriptive title of no more than 150 characters (20 words). Avoid the use of acronyms, quotation marks and upper case characters.)

Lightweight battery with more yield than a tonne of coal

A3. Person Participant Summary

	Person number	Family name	First name	Current organisation
1	1	Vaccaro	Joan	Griffith University
2	2	Uribarri	Luke	Lockheed Martin (US)
3	3	Hall	Kimberley	Dalhousie University, Canada
4	4	Barnett	Stephen	University of Glasgow, UK

	Relevant organisation for this proposal	Role
1	Griffith University	Chief Investigator
2	Lockheed Martin (US)	Partner Investigator
3	Dalhousie University, Canada	Partner Investigator
4	University of Glasgow, UK	Partner Investigator

A4. Organisation Participant Summary

	Organisation number	Short name	Name	Role
1	1	Griffith	Griffith University	Administering Organisation
2	2	Lockheed Martin	Lockheed Martin (US)	Partner Organisation
3	3	Dalhousie	Dalhousie University, Canada	Other
4	4	Glasgow Uni	University of Glasgow, UK	Other

A5. Summary of Proposal

(In no more than 750 characters (approx 100 words) of plain language, summarise aims, significance and expected outcomes.)

We aim to develop a device that is capable of converting waste heat into useful energy. Our recent breakthrough discovery of a new way to erase information will allow the device to operate using a battery that contains low entropy rather than energy. A battery of this kind can, in principle, have yields that are many times higher than currently available energy sources. We will design proof-of-principle demonstrations of the device and develop the supporting thermodynamical framework. The project will seed a new technology that has the potential to revolutionise the way we harness and use energy. It will enable Griffith University to take a pioneering role and help foster long term international collaborations.

A6. Summary of Project for Public Release

(In no more than 350 characters (approx 50 words), please provide a two-sentence descriptor of the purpose and expected outcome of the project which is suitable for media or other publicity material. Do not duplicate or simply truncate the 'Summary of Proposal'.)

The project aims to develop a device that uses a resource of low entropy to convert waste heat into useful energy. It will allow Australia to take a leading role in the development of a new technology that has the

potential to revolutionise the way we harness energy, and it will foster long term international research collaborations.

A7. Impact Statement

(In no more than 500 characters (approx 75 words), please outline the intended impact of the project. Refer to the Instructions to Applicants for further information.)

The project capitalises on our recent breakthrough research in thermodynamics. It will establish the groundwork for building a new technology with the potential to revolutionise the way we harness energy. The partnership with Lockheed Martin, the world's largest research and development company, will ensure that the social and economic benefits are realised as broadly as possible. It will give Australia a competitive advantage in the energy sector and opportunity to grow its manufacturing base.

PART B - Classifications and Other Statistical Information (LP140100797)

B1. Strategic Research Priorities

Does this proposal fall within one of the Strategic Research Priorities?

(Refer to the Instructions to Applicants for further information.)

Strategic Research Priority Selected

Yes

Select which of the Strategic Research Priorities the proposal falls within, and one or more of the relevant Priority Goals for the designated Strategic Research Priority.

	Strategic Research Priority Area	Strategic Research Priority Goal
1	Lifting productivity and economic growth	Maximise Australia's competitive advantage in critical sectors

B2. Field of Research (FOR)

	Field of Research (FOR)	Field of Research (FOR) Percent
1	020201 - Atomic and Molecular Physics	40
2	020304 - Thermodynamics and Statistical Physics	30
3	100799 - Nanotechnology not elsewhere classified	30

B3. Socio-Economic Objective (SEO-08)

	Socio Economic Objective (SEO)	Socio Economic Objective (SEO) Percent
1	970102 - Expanding Knowledge in the Physical Sciences	40
2	850499 - Energy Transformation not elsewhere classified	30
3	850702 - Energy Conservation and Efficiency in Transport	30

B4. Keywords

	Keywords
1	thermodynamics
2	information erasure
3	semiconductor heterostructures

B5. If the proposed research involves international collaboration, please specify the country/ies involved.

	International Collaboration Country Name
1	United States of America
2	Canada
3	United Kingdom

B6. How many PhD stipends are being requested in this Proposal?

1

C1. Please upload a Project Description as detailed in the Instructions to Applicants in no more than 8 A4 pages and in the required format.

Attached PDF

PROJECT TITLE: Lightweight battery with more yield than a tonne of coal

AIMS AND BACKGROUND

Background

Imagine a device that scavenges heat and converts it into useful mechanical work. If the work is later dissipated as heat, even that could be recycled by the device and converted back into useful work. Although it may appear to be unphysical, in fact the Laws of Thermodynamics do not forbid a device of this kind.

Indeed, our energy-scavenging device is really Maxwell's demon, taking heat from a single thermal reservoir and converting it into useful work [1]. The demon takes a gas, which is initially in thermal equilibrium, and separates hot molecules from cold ones to create two gases at different temperatures as illustrated in Fig. 1(a). A conventional heat engine then produces work from the two gases as in Fig. 1(b). Of course, the problem with Maxwell's demon is that it accumulates information about the speed of the molecules, and this information must be erased in order to return the demon to its initial state. As Landauer and Bennet showed, the erasure takes at least as much energy as is liberated by the demon, and so there is no overall energy gain and no violation of the second law [2–4].

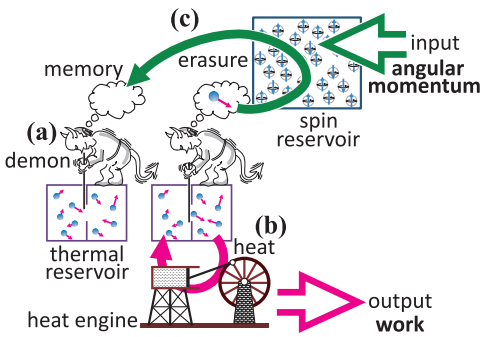

Figure 1: Maxwell's demon

But that is not the whole story. In a recent breakthrough, we (CI Vaccaro and PI Barnett) have shown that information can be erased without incurring an energy cost at all [5–7]. We found that a reservoir of energy-degenerate spins, which we call a *spin reservoir*, can absorb the entropy associated with the erased information as illustrated in Fig. 1(c). The energy degeneracy ensures that there is no energy cost associated with the increase in the entropy of the reservoir. Instead, the cost of erasure is a loss of spin angular momentum (spin polarization) of the spin reservoir. Our work shows that there is much more freedom in the way heat engines can operate than previously thought, and this opens up new opportunities that we want to exploit.

For example, if our energy-scavenging device incorporated the new erasure mechanism, it could be used in a remote environment to convert heat into useful work until it exhausted all its spin polarisation. Once that happened, the spin reservoir would need to be returned to base to have its spins realigned in some way, and presumably at a cost in energy. In this respect, the spin reservoir would operate somewhat like a rechargeable battery, but storing low entropy rather than energy. However, it may have an important advantage over a battery for the following reason. Each spin can liberate $kT\ln 2$ units of energy, where k is Boltzmann's constant and T is the temperature of the gas. If each spin is that of an electron and the gas is at room temperature, the ratio of the energy liberated per mass is $5,000\ \mathrm{MJ/kg}$, ignoring the mass of any substrate to carry the electrons. This is many times the ratios of $\sim 0.8\ \mathrm{MJ/kg}$ for a Li-ion battery and $24\ \mathrm{MJ/kg}$ for coal. Moreover, if the spin reservoir is replaced by a system with a Hilbert space of dimension D, it would have a capacity to liberate $kT\ln D$ units of energy. Although undoubtedly difficult to achieve in practice, a system weighing only a few grams but with a sufficiently-large dimension D could, in principle, liberate more energy than a tonne of coal. But even a modest improvement in the energy-to-mass ratio compared to current rechargeable battery technology could have significant repercussions for the way we harness and use energy in general.

Aims

Our long term goal is to exploit these ideas and develop a new energy technology based on the application of information erasure to thermodynamical systems. The current project will take the first steps towards that goal by developing models of heat engines based on the new erasure principle and exploring ways for *proof-of-principle demonstrations* using semiconductor heterostructures. As our work on erasure represents somewhat of a departure from convention, we will also examine extensions of the thermodynamical framework needed to support this work. In summary, the broad aims of this project are to:

1. **explore quantum dot heat engines operating on the new erasure mechanism**, and
2. **develop the supporting thermodynamical framework.**

The details of each aim are as follows.

Aim 1. Explore quantum dot heat engines operating on the new erasure mechanism

The **specific objectives** are to:

1.1 examine information erasure mechanisms in semiconductor heterostructures,

1.2 design heat engines using suitable erasure mechanisms, and

1.3 model their implementation in semiconductor heterostructures at Dalhousie University.

Excitons in semiconductor heterostructures have attracted a great deal of attention for developing optoelectronic applications over the last couple of decades [11] and devices for quantum computation [12–15]. As such, they represent an ideal technology for designing practical demonstrations of the new erasure mechanism. We will explore the possibilities for optical heat engines that use information erasure to liberate the thermal energy (heat) of a semiconductor system in the form of coherent radiation (optical work) or changes to external electric or magnetic fields (electromagnetic work). This work will be carried out in collaboration with PI Hall's experimental group at Dalhousie University, who will implement proof-of-principle demonstrations of heat engine models.

Aim 2. Develop the supporting thermodynamical framework

The **specific objectives** are to:

2.1 examine information erasure and heat extraction under non-equilibrium situations,

2.2 re-evaluate the laws of thermodynamics to include new kinds of reservoirs, and

2.3 redefine perpetual motion machines of the second kind.

The study of thermodynamical fluctuations has attracted a lot of interest in the last decade [21] including the erasure of information and the converse situation, heat extraction [22, 23]. We plan to examine information erasure and heat extraction for non-equilibrium situations for alternative reservoirs, such as our spin reservoir. A key feature of spin reservoirs is that entropy is maximised subject to the conservation of angular momentum in addition to energy [5–7]. This implies that the traditional statements of the first law of thermodynamics must be replaced with a statement about all pertinent conservation laws, not just energy. Because Landauer erasure is equivalent to the second law of thermodynamics [2, 3, 20], our results [5–7] not only call for a rethink of Landauer's principle [2] but also for a re-evaluation of statements of the second law, and along with them, definitions of perpetual motion machines of the second kind. We will undertake that re-evaluation and formulate the thermodynamical framework to support our Aim 1.

SIGNIFICANCE AND INNOVATION

Significance of research, and advancing knowledge and new technologies

The proposed study of erasure-based heat engines could have significant ramifications for energy technologies. The proof-of-principle demonstrations, if successful, would lay the foundation for new technology that has the potential to revolutionise the way we harness energy for mobile devices and at remote sites. The extended thermodynamical framework needed to support the new technology is no less significant. Energy conservation plays a dominant role in thermodynamics, but for our energy-degenerate spin reservoirs [5–7], energy conservation is satisfied trivially and the conservation of spin angular momentum plays a far more important role. Conventional treatments of thermodynamics have not allowed for this reversal of roles. We have shown [5–7] that spin reservoirs allow new processes such as information erasure without an an energy cost and new kinds of heat engines which are outside the scope of these conventional treatments. Given that spin reservoirs are now readily accessible with modern technology, the problem is all the more urgent. We aim to remedy this situation by re-evaluating and extending the laws of thermodynamics accordingly. It would be hard to overstate the significance of this work for the foundations of thermodynamics.

Meeting the objectives of the Linkage Projects scheme

Develop long term strategic alliances with research institutions and end-users for economic benefit. The project will help build a long-term strategic research collaboration between researchers at Griffith University, Dalhousie University (Canada) and Lockheed Martin Corporation (US) and maintain the long-term ($\sim$20 years) research collaboration between the 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. We aim to develop those technologies commercially in the longer term.

Pursue internationally competitive research. The project will also help Griffith University to pursue internationally leading research on the foundations of thermodynamics and applications of quantum dots.

Contributing to a pool of world class researchers. These collaborations will benefit the Research Fellow, PhD student and Honours students involved in the proposal, enabling them to take part in leading international

research and attend international conferences. The training of these researchers is an integral component of this proposal, which is of benefit to Australian innovation in general.

Potential for economic benefit to Australia

A potential outcome of the proposal is new technology for harnessing and using energy. This would help give Australia a competitive advantage in the energy supply sector through the opportunity to lead product development and to grow its manufacturing base. As such the proposal is directly aligned with the ARC's Strategic Research Priority of *Lifting productivity and economic growth* through the Priority Goal *Maximise Australia's competitive advantage in critical sectors*.

Benefits to Partner Organization

An important goal of the project is to design proof-of-principle demonstrations of new kinds of heat engines to be implemented in PI Hall's Ultrafast Quantum Control Lab at Dalhousie University, which has received considerable funding from PO Lockheed Martin over the last 5 years. The project will also establish the thermodynamical framework underpinning the operation of the new heat engines. Both the experimental demonstrations and the theoretical framework will assist in understanding how this new energy technology might be developed in the future. This will be of immense benefit to the participating organisations, including PO Lockheed Martin, who wish to develop commercial applications of the new energy technology explored in this project in the longer term.

APPROACH AND TRAINING

Methodology for exploring quantum dot heat engines based on the new erasure mechanism (Aim 1)

The new erasure mechanism we devised in [5–7] involves controlled spin exchanging interactions between the memory spin and the spin reservoir. But the information in the memory spin can also be erased through simple spin exchanging collision with the spin reservoir as follows. Imagine the two collection of spins as shown in Fig. 2(a). The spins in the reservoir is are polarized (aligned) whereas the spin of the memory is unknown.

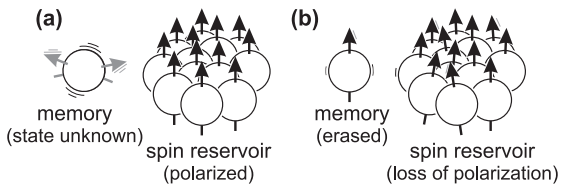

Figure 2: Erasure by spin exchanging collisions.

The situation after spin exchanging collisions between the reservoir and memory is shown in Fig. 2(b). The initial unknown orientation of the memory spin is now distributed among the spins of the reservoir and the memory spin is approximately in the spin up state. The contents of the memory has been erased at the expense of a loss of some of the polarization of the reservoir.

There are many situations in semiconductor heterostructures where such processes occur. An exciton gas in a state with a high degree of coherence represents a spin reservoir and a localized region of the gas which has been subjected to some additional preparation could represent the memory element. Elastic exciton-exciton collisions [25, 26] and even simple diffusion [27] would tend to redistribute the spin states of the excitons and thus erase the memory. Another possibility is suggested by the spin-flip scattering of excitons from Mn ions in GaMnAs recently observed at Dalhousie University [28, 29]. In this case the Mn ions could represent the memory elements and the excitons the spin reservoir. Yet another possibility is afforded by the spin interaction between excitons localized in quantum dots (memory) and photo-excited electrons in the surrounding bulk (spin reservoir) [30]. Other potential schemes also exist and will be explored.

We will use an erasure mechanism of this kind in the construction of a new heat engine to convert heat into optical work. As far back as 1959 Scovil and Schulz-DuBois showed that masers can be considered as the optical equivalents of heat engines [16]. The equivalence between coherent radiation and thermodynamical work was made concrete by Garbuny in 1977 [17]. This equivalence has also been used by Scully, Opatrny and others [18]. What will set our heat engine apart from previous types is that, with the aid of a Maxwellian demon, the new heat engine operates on a *single thermal reservoir* and *it employs a spin reservoir to erase the memory of the demon* in the following way.

Let the *working fluid* of the heat engine consist of a collection of "atoms" whose thermal energy is to be extracted as coherent light. Later we will consider how quantum dots could play the role of these atoms. Let the pertinent states of each atom be as illustrated in the energy level diagram in Fig. 3(a). The ground states have total angular momentum quantum number of $j = 1$ whereas the higher energy state has $j = 0$. Each

atom is initially in the state $j = 1$, $m_j = -1$. There is no magnetic field present and so magnetic sublevels are energy degenerate. An off-resonant Raman π pulse couples the two lower energy states via the higher energy state. In order to take part in the process an atom must supply the energy difference of ΔE. This means that only the hottest atoms take part and they each loose $Q = \Delta E$ of thermal energy in the process. For each atom that undergoes the Raman transition, the change in the energy of the coherent light is one photon lost (absorbed) from the σ_+ polarized field and one photon extra (stimulated emitted) in the σ_- polarized field. The energy of coherent light is increased by the difference in the ΔE energy of the two photons, i.e. heat Q is converted into optical work.

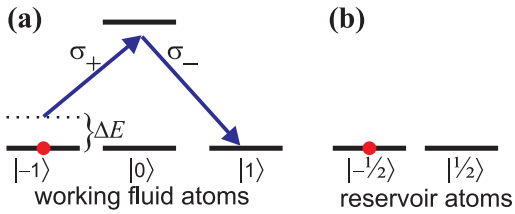

Figure 3: Off-resonant Raman pulse scheme to convert heat energy into coherent radiation for a single "atom".

The internal state of the atom plays the role of the memory of Maxwell's demon because it records which atoms were hot enough to take part in the Raman π pulse. This memory needs to be erased in order for the working fluid to return to its original configuration and complete a thermodynamic cycle. If it is erased using a mechanism like that described above, e.g. by interacting with a spin reservoir comprising atoms whose ground states have $j = 1/2$ as depicted in Fig. 3(b), then the erasure would occur at a cost of a loss of spin polarization of the spin reservoir and no dissipation of energy as heat. Inevitably the spin reservoir will also have a spatial degree of freedom at some temperature T so that during the erasure process it would rethermalize the working fluid to the same temperature. So effectively, *the heat $Q = \Delta E$ is extracted from the spin reservoir at a loss of its spin polarization*.

It is important to compare this new kind of heat engine with that of the conventional Carnot heat engine. In each Carnot cycle an amount of heat Q_1 is extracted from a hot reservoir at temperature T_1, of which W is converted into mechanical work and $Q_2 = Q_1 - W$ is dissipated into the cold reservoir at temperature T_2, giving an efficiency of $\epsilon = W/Q_1 = 1 - T_2/T_1$, as illustrated in Fig. 4(a). In the new heat engine, for Q heat extracted from the spin reservoir, optical work of $W = Q$ is produced giving an efficiency $\epsilon = W/Q = 1$. There is, however, a cost associated with this process in terms of a loss of spin polarization of the spin reservoir as illustrated in Fig. 4(b). Essentially, the new heat engine transfers entropy from the spatial degree of freedom of the spin reservoir to its spin degree of freedom. In the process the entropy is effectively decoupled from the heat which is released as optical work.

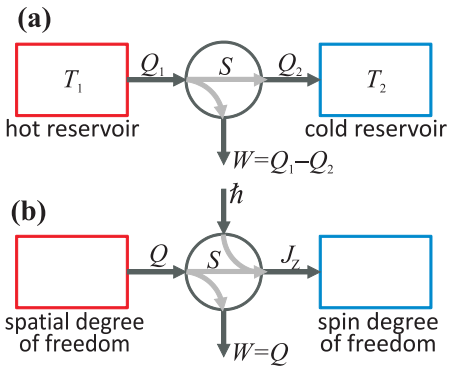

Figure 4: Comparison of (a) the Carnot cycle with (b) the cycle of the new heat engine.

One possibility for the "atoms" of the working fluid that immediately comes to mind is the GaAs quantum dot (QD) as illustrated in Fig. 5. The notation for the states in the figure is borrowed from Chen *et* al. [13] where the state $|e, h\rangle$ or $|e, h, e, h\rangle$ represents the spin state of the electron e and hole h in each exciton or biexciton, respectively, and g is the exciton vacuum. The z component of angular momentum of the exciton states are $-1\hbar$ for $|+1/2, -3/2\rangle$, $+1\hbar$ for $|-1/2, +3/2\rangle$ and $0\hbar$ for $|+1/2, -3/2, -1/2, +3/2\rangle$ as shown in the figure. This system therefore lends itself to the Raman pulse scheme of Fig. 3. One difference from Fig. 3 is that in Fig. 5 there is a fine structure splitting of δ between the two exciton states. Provided that $\Delta E > \delta$ heat can be converted into optical work in this system but with a loss in efficiency of the heat engine: for each cycle of the engine, heat $Q = \Delta E$ is converted into $W = \Delta E - \delta$ optical work and so the efficiency is $\epsilon = W/Q = 1 - \delta/\Delta E$, which is less than optimal. The focus of the Raman pulse lasers could include a number of QDs which would act in parallel as the working fluid.

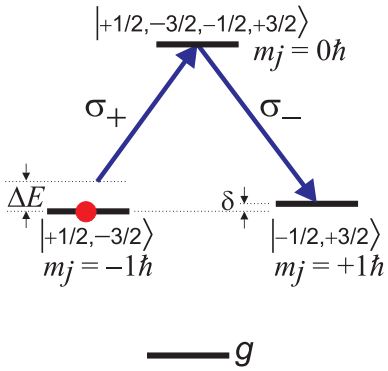

Figure 5: The equivalent of Fig. 3(a) for a GaAs quantum dot in the notation of Chen *et* al. [13].

To get some idea of the experimental parameters needed consider the following. For a temperature of 10K, the value of k_BT is of the order of 900μeV and a typical value of δ would be of the order 150μeV. Note that ΔE should be a deal larger than the laser linewidth. Taking a laser linewidth of 1meV places the lower bound $\Delta E \gtrsim 2meV \sim 2k_BT$. At this value of the detuning the heat extracted per QD each cycle is $Q = 2k_BT$ and the efficiency is $\epsilon = 1 - \delta/\Delta E \approx 0.92$.

Another, quite different, scheme is suggested by dynamic nuclear polarisation (DNP) where electrons are used to align the nuclear spins via a spin-spin interaction. The application of the technique to QD systems has been studied by Imamoglu *et* al. [31, 32] and Christ *et* al. [33]. In their models, the QD operates as a heat pump (or refrigerator) to cool the nuclear spins. As heat pumps are operationally the reverse of heat engines, this scheme has potential to work as a heat engine.

To operate as a heat engine, the nuclei would constitute the spin reservoir and the QD would be the working fluid. The nuclei and the QD would first be polarised into spin-up orientations by DNP according to the scheme in Ref. [31] and the magnetic field would be turned off. An off-resonant Raman π pulse by two right-circularly polarised lasers would be used as shown in Fig. 6 to couple the ground states with the energy difference ΔE supplied by heat from the substrate. After the pulse, a QD in the $\hat{e}^\dagger_\downarrow|0\rangle$ state represents stored memory which needs to be erased by returning the QD to the initial $\hat{e}^\dagger_\uparrow|0\rangle$ state. Spin exchanging interactions with the polarized nuclei would do this. The memory would be erased at the cost of spin angular momentum and no energy. As the process is repeated, heat of the substrate would be converted into coherent laser light.

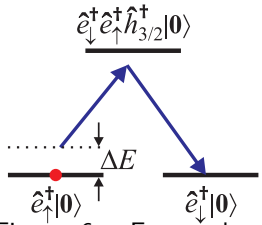

Figure 6: Energy levels and Raman π pulse couplings.

But there are many things to consider including modelling dynamics, laser linewidths, exciton lifetimes and decay modes and so on. There are also other possibilities for the working fluid including control techniques suggested by Imamoglu and collaborators [34], techniques investigated by Hall and collaborators [14, 15] and still others reviewed by Ramsay [35]. Investigating these things will form the main part of the project.

Methodology for developing the supporting thermodynamical framework (Aim 2)

We will begin by investigating the affect of fluctuations on information erasure and heat engines [22]. Our starting point will be recent work by Schumacher [23] who has derived the Jarzynski-Landauer equality for information erasure according to Landauer's principle as $\langle \exp(-\beta W - \Delta I)\rangle = 1$ where W is the work required to erase information represented by the change in Shannon entropy ΔI using a reservoir at temperature T where $\beta = 1/kT$. The probability that the required work W will be less than $kT\Delta I$ is given by $P(W < \Delta I/\beta - \epsilon) < \exp(-\beta\epsilon)$ for positive ϵ. Our focus will be on reservoirs with additional conversed quantities, such as our spin reservoir. A preliminary analysis shows that for our spin reservoir the corresponding Jarzynski equality is $\langle \exp(-\gamma J_z - \Delta I)\rangle = 1$ and $P(J_z < \Delta I/\gamma - \epsilon) < \exp(-\gamma\epsilon)$ where γ is the lagrange multiplier associated with the conservation of the z component of angular momentum J_z. We will explore this problem in detail using standard techniques.

Next we plan to extend the laws of thermodynamics to include the treatment of the conservation of quantities, such as spin angular momentum, in addition to energy. Our starting point will be based on the analysis by Jaynes [8]. Consider the statistical mechanics of a system which is characterised by a set of m physical quantities $f_k(x_i)$ for $k = 1, 2, \ldots m$ whose values depend on the statistical parameter x_i for $i = 1, 2, \ldots$ which has probability distribution p_i with $\sum_i p_i = 1$. The expectation value of f_k is given by $\langle f_k\rangle = \sum_i p_i f_k(x_i)$. The conservation of the quantity f_k implies that $\langle f_k\rangle$ is fixed. Maximising the entropy $S = -\sum_i p_i \ln p_i$ subject to fixed values of $\langle f_k\rangle$ and the normalisation of p_i gives

$$p_i = \exp\{-[\lambda_0 + \sum_{k=1}^{m} \lambda_k f_k(x_i)]\}\ , \qquad Z(\lambda_1, \cdots, \lambda_m) = \textstyle\sum_i \exp[-\sum_{k=1}^{m} \lambda_k f_k(x_i)]$$

where Z is the partition function and the λ_k are Lagrange multipliers. The Lagrange multiplier λ_k takes on role of temperature when f_k is the energy of the system. Jaynes identified $dQ_k = d\langle f_k\rangle - \langle df_k\rangle$ as being a quantity analogous to heat ("heat of the kth type") but he did not pursue these ideas in any detail. We plan to take up the challenge in this proposal. For example we immediately find that the first law of thermodynamics $dU = dQ + dW$ becomes $d\langle f_0\rangle = dQ_0 + \langle df_0\rangle$ where f_0 is energy of the system. Correspondingly the *extended first law* for conserved quantity f_k is $d\langle f_k\rangle = dQ_k + \langle df_k\rangle$. To appreciate the physical meaning of the terms λ_k, Q_k, $d\langle f_k\rangle$ and $\langle df_k\rangle$ we need to consider particular realisations of the system, such as our spin reservoir model

in Aim 1. At first sight one might expect that the *extended zeroth law* to be of the form "if two systems are in mutual equilibrium with respect to the quantity f_k then they have the same values of λ_k". But what if the two systems are not in equilibrium with respect to another quantity, say f_j? Presumably if brought into "contact" the systems would exchange the quantity f_j and so their distributions p_i and, consequently, the expectation value $\langle f_k \rangle$, would change. This contradicts the notion of equilibrium with respect to f_k. Just how the systems would behave in these situations is not yet known. A careful analysis of this problem is clearly needed and an appropriate definition of equilibrium, and the zeroth law, needs to be found.

We will also examine how our extension of Landauer's erasure principle affects various statements of the second law and consider new, broader statements that include the conservation of quantities other than energy. In particular, a heat engine based on the new erasure using a spin reservoir represents a *perpetual motion machine of the second kind*, according to conventional definitions (see e.g. [36]) because it is capable of extracting work from heat in a cyclical manner. The heat engine cannot work perpetually, however, as it depends on the continuous dissipation of spin angular momentum, and so the conventional definitions need to be revised. We will explore the implications of general information erasure mechanisms and the implication they have for perpetual motion machines, and then restate the definition of perpetual motion machines appropriately.

Research Plan

Aims and objectives	2014-5	2015-6	2016-7	V	LM	H	B
1. explore quantum dot heat engines							
1.1 explore erasure mechanisms				•	•	•	
1.2 model heat engines				•	•	•	
1.3 implementation at Dalhousie University					•	•	
1.3 adjust models				•	•		
1.3 examine new possibilities				•	•	•	
2. develop thermodynamical framework							
2.1 non equilibrium erasure and heat extraction				•	•		•
2.2 extending thermodynamic laws				•	•		•
2.3 2nd law and perpetual motion machines				•	•		•

Research plan showing timelines and main responsibilities of the project investigators where V=Vaccaro (CI Griffith), LM=Uribarri & Allen (PI & PO Lockheed Martin), H=Hall (PI Dalhousie), and B=Barnett (PI Glasgow).

Research Training

The work planned for Aim 1 will provide ideal training in computational physics for a PhD student and a number of Honours students. The modelling of quantum dots in different configurations is ideal for developing theoretical and numerical skills. The tasks will involve modelling the dynamics of various processes to determine the feasibility of heat engines proposals for ranges of physically realizable parameters and later comparing theoretical calculations with experimental results. The research will lead to a number of publications in international peer-reviewed journals jointly authored with the students.

RESEARCH ENVIRONMENT

Description of Research Environment

Griffith University is a world standard research-intensive university undertaking an array of research activities and ranked 11th out of 41 Australian institutions for the number of disciplines rated world standard or better in the ERA 2012 evaluation. It has an established, and growing, strength in the area of quantum physics research though its Centre for Quantum Dynamics (CQD). The Centre houses nodes of two ARC Centres of Excellence: the Centre for Quantum Computation and Communication Technology and the Centre for Coherent X-Ray Science, and is a member of the international Max Planck Centre for Attosecond Science. In the last 8 years Griffith has expanded CQD with additional strategic appointments in the areas of quantum optics and information, quantum information in ionic systems, and ultrafast atomic processes. Griffith has invested millions of dollars of cash directly into CQD through startup grants and specialised laboratory renovations. CQD researchers are the primary contributors to Griffith University's ERA ranking of 4 in Physics "well above world standard" (ARC Field of Research code 02) and Quantum Physics (FoR code 0206). The theoretical and experimental research programs in CQD are well above the 'critical mass' for providing a positive and enthusiastic research environment in which to undertake the research in this proposal.

Dalhousie University is a member of the U15, a group of 15 of Canada's most research-intensive universities,

and receives more than CAD140,000,000 in external research funding annually. It has received over CAD2,000,000 in funding from Lockheed Martin Corporation to develop PI Hall's Ultrafast Quantum Control Lab in the Department of Physics and Atmospheric Science. The internationally-leading faculty staff in the Department and the well-equipped laboratory provide a world class research environment for undertaking the experimental aspects of the project.

Glasgow University is ranked 51st in the world by the Quacquarelli Symonds (QS) World University Rankings. The School of Physics and Astronomy is a vibrant centre of research rated as excellent in the last UK research assessment exercise (e.g. 60% of staff were 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.

Griffith University's Strategic Research Plan

The proposal's fundamental research into the laws of thermodynamics, its development of new kinds of heat engines, and its potential for commercialisation of the resulting new technology fit squarely within Griffith University's *2013-2017 Research Plan* which carries the mission "to engage in outstanding scholarship that makes a major contribution to society and to produce ground breaking research". The collaboration with PO Lockheed Martin fits within Strategy S1.11 of the *2013-2017 Research Plan*: "Leverage commercial research activities to support ongoing research" and the training of a PhD student is in accord with Goal 3 of the *2013-2017 Research Plan*: "To increase the number of HDR commencements and completions".

Dissemination

We envisage a range of scholarly publications in international peer-reviewed journals. We intend to publish the most significant results in leading journals such as Nature, Nature Physics and Physical Review Letters and publish other important work in journals such as Physical Review A, Proceedings of the Royal Society A, Journal of Physics A and so on. We will also present our findings at international conferences and workshops. Our work will also be communicated to the wider public through press releases by our respective External Relations Offices as well as talks to high school students as part of our Institutions' public engagement and outreach programs.

PARTNER ORGANISATION COMMITMENT AND COLLABORATION

PO Lockheed Martin 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 the awarding of seed funding of **$171,707** from August 2013 to July 2014 to CI Vaccaro. It is involved in this proposal through its funding to Griffith University principally to support teaching relief for CI Vaccaro and part funding of a Research Fellow, 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. PO Lockheed Martin will benefit from the deeper understanding of energy storage systems provided by the basic research undertaken in this project.

This projects entails the design of proof-of-principle demonstrations and the formulation of the supporting thermodynamical framework 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 the Partner Organisation and Griffith University.

ROLE OF PERSONNEL

CI Vaccaro. Associate Professor Joan Vaccaro is the Project Leader responsible for managing the project budget, detailed planning and results communication at Griffith University. She has wide expertise in fundamental aspects of quantum physics, including quantum information theory and information erasure, and will play a leading role in dealing with conceptual issues that will arise across all aspects of the project. She also brings to the collaboration expertise in the analytical and numerical modelling of atomic systems and their manipulation with laser fields, which will be invaluable for modelling the dynamics of heat engine proposals.

PI Uribarri & other personnel at PO Lockheed Martin. Dr. Luke Uribarri, 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 CI Vaccaro, PI Hall and Lockheed Martin. Dr Ned Allen, Chief Scientist, will provide guidance regarding potential new applications and extensions of the core concepts. A Technical Assistant will supervise contractual and budgetary arrangements and assist with protection of intellectual property generated by the Project.

PI Hall. Associate Professor Kimberley Hall (Dalhousie University) has extensive expertise in experimental semiconductor heterostructure research and holds a Canada Research Chair in Ultrafast Science. She has received over CAD2,000,000 from Lockheed Martin to pursue experimental research in quantum technologies in semiconductor heterostructures. She will provide invaluable information regarding the semiconductor heterostructures systems and experimental techniques that are feasible for her Lab. She will play a pivotal role in assessing the practicality of heat engines proposals and therefore have a major input in what proposals undergo extensive modelling. She will also play an important role in providing feedback on the actual experimental implementations, in guiding any necessary adjustments to the models and proposing new possibilities.

PI Barnett. Prof Stephen Barnett (Glasgow University) 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 research grants awarded by various funding agencies including the Engineering and Physical Sciences Research Council (EPSRC) in the UK. He will provide creative insight and his expertise theoretical physics in collaboration with CI Vaccaro in achieving Aim 2. He will also act as mentor to CI Vaccaro.

Research Fellow and Students. The work on semiconductor heterostructures will require extensive modelling (analytical and numerical) by a full time Research Fellow hired from this grant. CI Vaccaro will manage the RF employed for this work at Griffith University. Vaccaro and the RF will supervise a PhD and Honours students at Griffith University.

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C2. Medical and Dental Research Statement

(If applicable, in no more than 750 characters (approx. 100 words), please justify why this Project does not constitute Medical and Dental Research as defined on the ARC website. Refer to the Instructions to Applicants for further information.)

Not applicable.

PART D - Partner Organisation Details (Lockheed Martin (US))

D1. Organisation contact details

Title

Dr

Family Name

Uribarri

First Name

Luke

Second Name

Alexander

Position

Deputy to the Chief Scientist

Phone

+1 610-354-6353

Email Address

luke.uribarri@lmco.com

D2. Organisation postal address

(The postal address will be filled out for you automatically. To update the organisation's postal address, please contact the ARC at rms@arc.gov.au.)

Postal Address Line 1

PO Box 748

Locality

Fort Worth

State

TX

Postcode

76101

Country

United States of America

D3. Organisation ABN and Type

(These organisation details will be filled out for you automatically. To update these details, please contact the ARC at rms@arc.gov.au.)

Web page address

www.lockheedmartin.com

ANZSIC

Other Transport Equipment Manufacturing

Organisation type

International Company Industry Body

D4. 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

D5. Type of Partner Organisation

Is this Partner Organisation an Exempt Community Organisation, an Exempt Herbarium, an Exempt Museum, an Exempt Non-Profit Organisation, an Exempt Registered Charity or an Exempt Start-up?

(Please refer to Section 6.3.9 of the Linkage Projects Funding Rules for funding commencing in 2014 and the Instructions to Applicants for further information.)

No

Type of Exempt Organisation

Not applicable for this candidate

D6. Evidence of collaboration with the Administering Organisation and the alignment of the Project with the Partner Organisation's strategic plan.

(In no more than one A4 page, provide evidence of new or on-going collaboration between the Partner Organisation and the Administering Organisation, including details of how the Project fits into the Partner Organisation's strategic plan and how it will add value to the Partner Organisation.)

D6. Evidence of collaboration with the Administering Organisation and the alignment of the Project with the Partner Organisations strategic plan

PI Uribarri, Deputy to the Chief Scientist at Lockheed Martin Corporation, initiated contact with CI Vaccaro in mid 2012 regarding research that she and PI Barnett had recently published [J.A. Vaccaro and S.M. Barnett, "Information erasure without an energy cost", *Proc. R. Soc. Lond. A* **467**, 1770-1778 (2011)]. The Chief Scientist of Lockheed Martin, Dr Ned Allen, then visited Griffith University in November 2012 to discuss the prospect of developing the research in collaboration with PI Hall at Dalhousie University using semiconductor heterostructures. Lockheed Martin have been supporting PI Hall and her Ultrafast Quantum Control Lab at Dalhousie University, Halifax, Canada with over CAD2,000,000 in funding since 2008. CI Vaccaro was asked to submit a proposal on the feasibility of the experimental research. The proposal was accepted and Lockheed Martin awarded a one-year research contract valued at **$171,000** from August 2013 to July 2014. CI Vaccaro visited PI Hall's Ultrafast Quantum Control Lab in August 2013 to discuss the facilities and the range of semiconductor heterostructures that PI Hall has access to. Communication with Lockheed Martin through PI Uribarri and other Lockheed Martin staff has been ongoing. The current Linkage Project represents a commitment to a long-term research collaboration between CI Vaccaro, PI Hall and Lockheed Martin. Chief Scientist Dr Allen provides overall vision for the collaboration and PI Uribarri and other Lockheed Martin staff provide more direct involvement with the project.

As one of the worlds largest technology companies, with annual turnover of $50B, Lockheed is deeply involved in research and development in a multitude of areas, including aerospace, security, energy storage. Modern living is hindered by the limitations of the batteries used in everyday life, for transportation needs, electronics and defense systems. Nanotechnology enables significant performance and technology improvements in the areas of energy storage. The unprecedented control of materials offered by nanotechnology opens up new possibilities for harnessing energy that would revolutionize the way we use energy in mobile devices and in remote locations.

The intellectual property generated in this Project has significant commercial development potential in the rechargeable battery market. In the course of negotiating the previous contract, mutually satisfactory arrangements were reached regarding the balance between commercial and research imperatives, including the licensing of intellectual property.

D7. 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 certification letter, signed by the CEO or delegate. Refer to Section 6.2.6 of the Linkage Projects Funding Rules for funding commencing in 2014 for details of the required content for this letter.)

Attached PDF

Lockheed Martin Corporation
6801 Rockledge Drive, Bethesda, MD 20817
(301) 897-6000

October 24, 2013

Professor Aidan Byrne
Chief Executive Officer
Australian Research Council
GPO Box 2702
Canberra ACT 2601
Australia

Dear Professor Byrne,

I am writing to express the full support of Lockheed Martin Corporation as the Partner Organization for Linkage Project LP140100797, "Lightweight battery with more yield than a tonne of coal."

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, employs over 750 people across all of the Australian states and territories, and had turnover exceeding A$200 million in 2012.

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 outlined in our first meetings with Associate Professor Vaccaro was of a technology of fantastic impact and but unclear development path. We are very pleased with the direction that A/Prof. Vaccaro has taken the concept in our relationship 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 2014, 2015, and 2016:

2014:	2015:	2016:
• Cash: AU$110,000 • In-kind: AU$75,500	• Cash: AU$119,000 • In-kind: AU$75,500	• Cash: AU$121,000 • In-kind: AU$75,500

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 (10%), 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

D8. Partner Investigator participating on this Proposal for this Partner Organisation.

Dr Luke Uribarri

PART E - Project Cost (LP140100797)

E1. What is the proposed budget for your project?

(Please provide details of the budget proposed for your project.)

Proposal Funding Summary

Total requested budget: $255409

Year 1

Description	ARC	AdminOrg		Other		PO	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Direct Cost	97003	0	89505	0	56154	109640	75500
Personnel	71803	0	89505	0	56154	58000	67500
CI - Joan Vaccaro LD.4 @ 0.5 FTE + 28% oncosts	0	0	89505	0	0	0	0
PI - Stephen Barnett UK Professor @ 0.1 FTE	0	0	0	0	19354	0	0
PI - Kimberley Hall Canadian A/Prof @ 0.25 FTE	0	0	0	0	36800	0	0
PI - Luke Uribarri @ 0.1FTE	0	0	0	0	0	0	25000
PO - Ned Allen, Chief Scientist @ 0.05 FTE	0	0	0	0	0	0	30000
PO - Technical Assistant @ 0.05 FTE	0	0	0	0	0	0	12500
Research Fellow Level 1.5 @ 1.0 FTE +28% oncosts	43075	0	0	0	0	58000	0
PhD scholarship	28728	0	0	0	0	0	0
Teaching Relief	0	0	0	0	0	43640	0
CI Joan Vaccaro 0.4 FTE for 36 months	0	0	0	0	0	43640	0
Equipment	10600	0	0	0	0	5000	0
Computer upgrades and software	10600	0	0	0	0	5000	0
Travel	14600	0	0	0	0	3000	8000
Travel for CI and RF: Brisbane-Glasgow-Halifax (economy) return, $150/day for accommodation, $50/day for meals	14600	0	0	0	0	3000	0
Travel for PO staff: US-Brisbane (economy) return, $150/day for accommodation, $50/day for meals	0	0	0	0	0	0	8000

Year 2

Description	ARC	AdminOrg		Other		PO	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Direct Cost	78703	0	89505	0	56154	118637	75500
Personnel	60803	0	89505	0	56154	69000	67500
CI - Joan Vaccaro LD.4 @ 0.5 FTE + 28% oncosts	0	0	89505	0	0	0	0
PI - Stephen Barnett UK Professor @ 0.1 FTE	0	0	0	0	19354	0	0
PI - Kimberley Hall Canadian A/Prof @ 0.25 FTE	0	0	0	0	36800	0	0
PI - Luke Uribarri @ 0.1FTE	0	0	0	0	0	0	25000
PO - Ned Allen, Chief Scientist @ 0.05 FTE	0	0	0	0	0	0	30000
PO - Technical Assistant @ 0.05 FTE	0	0	0	0	0	0	12500

Description	ARC	AdminOrg		Other		PO	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Research Fellow Level 1.5 @ 1.0 FTE +28% oncosts	32075	0	0	0	0	69000	0
PhD scholarship	28728	0	0	0	0	0	0
Teaching Relief	0	0	0	0	0	46637	0
CI Joan Vaccaro 0.4 FTE for 36 months	0	0	0	0	0	46637	0
Equipment	3300	0	0	0	0	0	0
Computer upgrades and software	3300	0	0	0	0	0	0
Travel	14600	0	0	0	0	3000	8000
Travel for CI and RF: Brisbane-Glasgow-Halifax (economy) return, $150/day for accommodation, $50/day for meals	14600	0	0	0	0	3000	0
Travel for PO staff: US-Brisbane (economy) return, $150/day for accommodation, $50/day for meals	0	0	0	0	0	0	8000

Year 3

Description	ARC	AdminOrg		Other		PO	
	Cash	Cash	In-kind	Cash	In-kind	Cash	In-kind
Direct Cost	79703	4900	89505	0	56154	120770	75500
Personnel	61803	0	89505	0	56154	68000	67500
CI - Joan Vaccaro LD.4 @ 0.5 FTE + 28% oncosts	0	0	89505	0	0	0	0
PI - Stephen Barnett UK Professor @ 0.1 FTE	0	0	0	0	19354	0	0
PI - Kimberley Hall Canadian A/Prof @ 0.25 FTE	0	0	0	0	36800	0	0
PI - Luke Uribarri @ 0.1FTE	0	0	0	0	0	0	25000
PO - Ned Allen, Chief Scientist @ 0.05 FTE	0	0	0	0	0	0	30000
PO - Technical Assistant @ 0.05 FTE	0	0	0	0	0	0	12500
Research Fellow Level 1.5 @ 1.0 FTE +28% oncosts	33075	0	0	0	0	68000	0
PhD scholarship	28728	0	0	0	0	0	0
Teaching Relief	0	0	0	0	0	49770	0
CI Joan Vaccaro 0.4 FTE for 36 months	0	0	0	0	0	49770	0
Equipment	3300	0	0	0	0	0	0
Computer upgrades and software	3300	0	0	0	0	0	0
Travel	14600	4900	0	0	0	3000	8000
Travel for CI and RF: Brisbane-Glasgow-Halifax (economy) return, $150/day for accommodation, $50/day for meals	14600	0	0	0	0	3000	0
Travel for PhD student: Brisbane-Europe/Nth America (economy) return, $150/day for accommodation, $50/day for meals, $500 conference fee	0	4900	0	0	0	0	0
Travel for PO staff: US-Brisbane (economy) return, $150/day for accommodation, $50/day for meals	0	0	0	0	0	0	8000

Other Summary

	Year 1		Year 2		Year 3	
	Cash	**In-kind**	**Cash**	**In-kind**	**Cash**	**In-kind**
Dalhousie University, Canada	0	36800	0	36800	0	36800
University of Glasgow, UK	0	19354	0	19354	0	19354
Total	**0**	**56154**	**0**	**56154**	**0**	**56154**

Partner Organisation Summary

	Year 1		Year 2		Year 3	
	Cash	**In-kind**	**Cash**	**In-kind**	**Cash**	**In-kind**
Lockheed Martin (US)	109640	75500	118637	75500	120770	75500
Total	**109640**	**75500**	**118637**	**75500**	**120770**	**75500**

PART F - Budget Justifications (LP140100797)

F1. Justification of funding requested from the ARC

(In no more than two 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 Part E of this Proposal. Each page of the PDF should be titled 'F1 – Justification of funding requested from the ARC'.)

F1 – Justification of funding requested from the ARC

PERSONNEL

Research Fellow Level 1.5 @ 1.0 FTE + 28% on costs

The objectives of Aim 1 are to develop models of erasure and associated heat engines based on spin reservoirs that are able to be realised experimentally in PI Hall's laboratory at Dalhousie University. This will require extensive analytical and numerical modelling of semiconductor heterostructures undergoing spin-changing interactions and being manipulated by laser and magnetic fields. To maximise the opportunity for success of the project a full time researcher funded by this grant is needed for this work. The person would need a broad range of knowledge in Atomic, Molecular and Optical physics as well as skills in numerical modelling. We would expect a researcher who has a PhD in a topic involving laser atomic spectroscopy or quantum dots research to have the prerequisite knowledge and skills. Accordingly we plan to hire a Research Fellow at Level 1.5 to carry out this work for a total cost (including oncosts) of $303,226 over 3 years. The PO will contribute $195,000 towards this cost.

We are requesting the balance of **$108,226** from the ARC.

PhD scholarship @ 1.0 FTE

The thermodynamical issues being considered in this project are at the cutting edge of research into the quantum properties of nanoscopic systems. With the interest in such systems expected to grow significantly world-wide, and with the wealth of new physics likely to be uncovered, the project area is an ideal area to train a new student entering into theoretical quantum research.

We are requesting support for a PhD scholarship to the total value of **$86,184** from the ARC over the 3 year term of the project.

EQUIPMENT

Computer upgrades and software

The project will require analytical analysis and extensive computer modelling. Griffith University maintains MATLAB site licences which will provide the main tool for the numerical modelling. However, it will be essential for the success of the project for the Research Fellow, PhD student and CI to have licences for symbolic processing (Mathematica $1100/year x 3 for 3 years), scientific writing (Scientific Word $550 x 3), Fortran development package (Intel Fortran Studio XE $1000 x 3) and plotting (SigmaPlot $550 x 3) software packages. Also the standard computer equipment (currently Dell OptiPlex 9020 4GB i5 Desktop pc) supplied by Griffith University, while more than satisfactory for routine office tasks is not adequate for intensive computational work. Accordingly we are requesting funds of $2,000 x 3 to upgrade the equipment to higher specification (increased RAM to 16GB with i7 core processor). The total cost is $22,200 of which $5,000 will be contributed by PO Lockheed Martin.

We are requesting the balance of **$17,200** from the ARC.

TRAVEL

Travel for CI and RF: Brisbane-Glasgow-Halifax (economy) return, $150/day for accommodation, $50/day for meals

This project is a collaborative venture that combines the talents and expertise of its Investigators from four Organisations in four 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 fulfil the plans for dissemination, it is important that results of the research are publicised at International Conferences and Workshops. Accordingly, we are requesting funds to cover six economy-fare return trips between Australia, the UK and Canada and associated living expenses for two weeks over the duration of the project. To visit both PI Barnett in Glasgow and and PI Hall in Halifax from Brisbane involves at least 7 different flights (e.g. Brisbane-London-Glasgow-London-Toronto-Halifax-Toronto-Brisbane) and costs an estimated $6,000 for an economy fare. We estimate that the accommodation

and meals for visits lasting 7 days at each of Glasgow and Halifax gives to cost $2,800 per trip. This gives an estimated total cost of $8,800 per trip. We plan to coordinate the travel so that the CI and RF may also present findings at international conferences and workshops, such as the International Conference on heat Transfer and Fluid Flow in Prague, Czech Republic during August 2014. The total cost of international travel is $52,800. PO Lockheed Martin will contribute $9,000 towards this cost.

We are requesting the balance of **$43,800** from the ARC.

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

(In no more than two A4 pages and within the required format, provide a justification of how non-ARC contributions will support the proposed project. Use the same headings as in the Description column in the budget at Part E of this Proposal. Contributions by Partner Organisations should be highlighted and attributed to specific Partner Organisations. Each page of the PDF should be titled 'F2 – Justification of Partner Organisation and other non-ARC contributions'.)

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

ADMINISTERING ORGANISATION

PERSONNEL

CI - Joan Vaccaro LD.4 @ 0.5 FTE +28% oncosts

Assoc. Prof. Joan Vaccaro will lead the project, supervise the Research Fellow and the PhD and Honours students and collaborate with PI Hall on the tasks for Aim 1, and collaborate with PI Barnett on the tasks for Aim 2. She is co-author (with PI Barnett) of the ground-breaking papers (Refs. [5-7] in C1 Project) on the erasure of information without an energy cost which are central to this project. Her theoretical expertise and creative input is essential for driving the Project at Griffith University.

The total value of in-kind contributions is approximately **$268,515** over 3 years.

TRAVEL

Travel for PhD student: Brisbane-Europe/Nth America (economy) return, $150/day for accommodation, $50/day for meals, $500 conference fee

Attending and presenting results of research at an international conference is an integral part of the training of the PhD student. Griffith University provides research students up to $6000 over three years to attend conferences and present their work. We have included one trip of 7 days with economy fares of $3,000 for attending a conference in Europe or North America in Year 3.

The total value of the cash contributions is **$4,900** in year 3.

OTHER ORGANISATIONS

PERSONNEL

PI - Kimberley Hall Canadian A/Prof @ 0.25 FTE

Assoc. Prof. Kimberley Hall will play a key role towards achieving Aim 1 of the Project as the experimentalist. She will provide technical information regarding the semiconductor heterostructures systems and experimental techniques that are feasible for her Lab at Dalhousie University. She will also implement proof-of-principle demonstrations of heat engines that are developed within the Project in her Lab and provide experimental results to verify the theoretical models.

PI - Stephen Barnett UK Professor @ 0.1 FTE

Prof. Steven Barnett is a key member of the theoretical team. He is co-author (with CI Vaccaro) of the ground-breaking papers (Refs. [5-7] 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 the task for Aim 2. He will also provide mentorship in both research and project management for CI Vaccaro.

The total value of these in-kind contributions is approximately **$168,000** over 3 years.

PARTNER ORGANISATION: Lockheed Martin

PERSONNEL

PI - Luke Uribarri @ 0.1 FTE

Dr Luke Uribarri, Deputy to the Chief Scientist at Lockheed Martin, will provide intellectual input into both Aims of the project through his knowledge of energy storage systems based on quantum thermodynamics and non-linear optical properties of quantum dots. He will act as the main contact at PO Lockheed Martin and will coordinate activity at Griffith University with the experimental implementation by PI Hall at Dalhousie University. He will also provide key advice regarding technology transfer issues which will enhance the long term economic impact of the Project.

The total in-kind contribution is **$75,000** over 3 years.

PO - Ned Allen, Chief Scientist @ 0.05 FTE

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.

The total in-kind contribution is **$90,000** over 3 years.

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

PO - Technical Assistant @ 0.05 FTE

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

The total in-kind contribution is **$37,500** over 3 years.

Research Fellow Level 1.5 @ 1.0 FTE +28% oncosts

As mentioned in Section F1, to maximise the opportunity for success of the project a full time researcher funded by this grant is needed and we plan to hire a Research Fellow at Level 1.5 to carry out this work for a total cost (including oncosts) of $303,226 over 3 years. Part of the funding is being requested from the ARC.

A cash contribution from PO Lockheed Martin of **$195,000** will cover the balance of the cost.

TEACHING RELIEF

CI - Joan Vaccaro 0.4 FTE for 36 months

Aim 2 of the proposal is to provide the thermodynamical framework that underpins the design of heat engines and proof-of-principle tests that will be carried out in meeting Aim 1. Developing that framework involves deep conceptual issues concerning new ways of thinking about entropy and information and their relation to physical systems, the meaning of different kinds of equilibrium with respect to various quantities of interest (energy exchange, angular momentum exchange, and so on), notions analogous to temperature and heat for other conserved quantities and fluctuations away from equilibrium. This work will be undertaken by CI Vaccaro. At the same time CI Vaccaro will be exploring potential semiconductor heterostructure systems as spin reservoirs that could be used for information erasure mechanism and implement erasure-based heat engines, and supervising the Research Fellow who will be heavily involved in modelling erasure mechanisms and heat engines and supervising the PhD and Honours students. To deliver the project outcomes as quickly as possible and optimise the success of the project, it is essential that CI Vaccaro contribute a significant proportion of her time to the project. We estimate that she will need to spend 0.5 of her time on this project. She can commit 0.1 FTE directly. The balance will require teaching relief to allow CI Vaccaro to contribute an additional 0.4 FTE to the project. The cost of the teaching relief is 0.4 FTE of the salary (with 28% oncosts) of a Lecturer at level LB over the course of the project.

A cash contribution by PO Lockheed Martin of approximately **$140,000** will cover this cost.

TRAVEL

Travel for CI and RF: Brisbane-Glasgow-Halifax (economy) return, $150/day for accommodation, $50/day for meals

It is essential that the Investigators meet in person at least annually to coordinate the research and regularly attend International Conferences and Workshops to disseminate results. We are requesting funds to cover six economy-fare return trips between Australia, the UK and Canada and associated living expenses for two weeks over the duration of the project. The total cost of international travel is $52,800 (details are given in F1). PO Lockheed Martin will contribute a portion towards this cost with the balance requested from the ARC.

The total cash contribution by PO Lockheed Martin for this is **$9,000**.

Travel for PO Staff: US-Brisbane (economy) return, $150/day for accommodation, $50/day for meals

Lockheed Martin project staff will visit Griffith University at the level of two visits per year to coordinate research, communicate results and contribute to the project. With airfares estimated at $3,000, the cost for 5 days accommodation and meals is $8,000 per year.

The total in-kind contribution is **$24,000** over 3 years.

G1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Associate Professor

Family Name

Vaccaro

First Name

Joan

Second Name

Alfina

Person identifier

A1241678

Role

Chief Investigator

G2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

Griffith University

Postal Address Line 2

170 Kessels Road

Locality

Nathan

State

QLD

Postcode

4111

Country

Australia

G3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to ARC College or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

G4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 July 2014.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

G5. Are you an Indigenous Participant?

Indigenous Participant

No

G6. PhD Qualification

Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

03/12/1990

G7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	1990	Theoretical Physics	Griffith University

	Degree/Award	Year	Discipline/Field	Organisation Name
2	BSc(1st Class Hon)	1985	Physics	Griffith University
3	BSc	1984	Physics and Applied Maths	Griffith University

	Country
1	Australia
2	Australia
3	Australia

G8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Associate Professor	Griffith University	School of Biomolecular and Physical Sciences	2011
2	Senior Lecturer	Griffith University	School of Science	2005
3	Reader in Physics	University of Hertfordshire	Department of Physics, Astronomy and Mathematics	2000

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes
2	Permanent	Full Time	No
3	Permanent	Full Time	No

G9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 July 2014 and beyond; for PIs it will generally be their main employer as at 1 July 2014).)

Organisation Name

Griffith University

Type of Affiliation

Employee

G10. Time commitment (%FTE) to this Project

50

G11. Research Opportunity and Performance Evidence (ROPE)

G11.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i) Years since graduating with a PhD: 22.

(ii) Research opportunities:
3 years as a lecturer (research+teaching) of information systems in a Business Faculty in Australia (1991-1994), 4 years in physics postdoctoral positions (research only) in Germany and the UK (1994-1997), 15 years lecturing (research+teaching) physics in the UK (1997-2005) and Australia (2005-2013).

(iii) Role in last 10 years:
standard teaching and research profile (nominally 40% teaching, 40% research, 20% administration)

(iv) Career Interruptions: None

(v) Research Mentoring and Facilities:
Griffith University offers research mentoring by a senior research academic as part of its annual academic staff review which is described in its Academic Staff Review Policy and Procedures document number 2008/0021022. I regularly consult Emeritus Professor David Pegg FAA and Professor Howard Wiseman FAA, both at Griffith University, for advice concerning research. They are my informal mentors. My research has also been supported by a Griffith University Research Grant of approximately $10,000 (2009-2010) for computer equipment and travel. I recieve annual funding of approximately $3000 for travel, books and so on from the School of Biomolecular and Physical Sciences and the research Centre for Quantum Dynamics. The research facilities available to me are more than adequate to carry out the research planned in this proposal.

(vi) Other aspects:
I moved from the University of Hertfordshire, UK to Griffith University in 2005. In addition to the normal preparation of new lectures after arriving at Griffith University, I was subsequently required to develop new lectures for courses taught by retiring staff and a new Accelerated Honours degree program. In the first few years I developed over 180 new lectures which limited my time for research. Following a long period of deliberation, I transition from Male to Female in January 2007. The period of a few years before and after my transition were significantly less productive in terms of my research outputs.

G11.2. Recent significant publications and ARC grants (since 2003)

(Please attach a PDF with a list of your recent significant publications and ARC grants most relevant to this Proposal (10 Pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

A/Prof Joan A Vaccaro

Part 1 Publications

Asterisked publications are relevant to the current proposal. Journal Impact Factors are from Thomson Reuters Journal Citation Reports.

Scholarly Book

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

Refereed Journal Articles

2. H.M. Wiseman and **J.A. Vaccaro**, "The entanglement of indistinguishable particles shared between two parties", *Phys. Rev. Lett.* **91**, 097902 (2003).
   [103 citations] **[Journal Impact Factor: 7.9]**

3. Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, "Experimental demonstration of quantum source coding", *Phys. Rev. Lett.* **91**, 217902 (2003),
   [12 citations] **[Journal Impact Factor: 7.9]**

4. **J.A. Vaccaro**, Y. Mitsumori, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, "Quantum data compression", *Lecture Notes In Computer Science*, **2827**, 98-107 (2003).

5. A.D. Greentree, D. Richards, **J.A. Vaccaro**, A. Durrant, S. de Echaniz, D. Segal and J. Marangos, "Intensity-dependent dispersion under conditions of electromagnetically induced transparency in coherently prepared multistate atoms" *Phys. Rev. A* **6**7, 023818 (2003).
   [28 citations] **[Journal Impact Factor: 3.0]**

6. **J.A. Vaccaro**, F. Anselmi and H.M. Wiseman, "Entanglement of identical particles and reference phase uncertainty", *Int. J. Quant. Inf.*, **1**, 427-441 (2003),

7. S.J. Jones, H.M. Wiseman, S.D. Bartlett, **J.A. Vaccaro**, D. Pope, "Entanglement and Symmetry: A Case Study in Superselection Rules, Reference Frames, and Beyond", *Phys. Rev. A* **74**, 062313 (2006).
   [10 citations] **[Journal Impact Factor: 3.0]**

8. **J.A. Vaccaro**, J. Spring and A. Chefles, "Quantum protocols for anonymous voting and surveying", *Phys. Rev. A* **75**, 012333 (2007),
   [30 citations] **[Journal Impact Factor: 3.0]**

9. **J.A. Vaccaro**, F. Anselmi, H M. Wiseman and K. Jacobs, "Tradeoff between extractable mechanical work, accessible entanglement, and ability to act as a reference system, under arbitrary superselection rules", *Phys. Rev. A* **77**, 032114 (2008).
   [10 citations] **[Journal Impact Factor: 3.0]**

10. G.A. White, **J.A. Vaccaro**, and H.M. Wiseman, "Optimal reference states for maximum accessible entanglement under the local particle number superselection rule", *Phys. Rev. A* **79**, 032109 (2009).
    [2 citations] **[Journal Impact Factor: 3.0]**

* 11. **J.A. Vaccaro** and S.M. Barnett, "Information erasure without an energy cost", *Proc. R. Soc. A* **467**, 1770-1778 (2011). (Eprint http://arxiv.org/abs/1004.5330)
    Ranked A* by ERA 2010 **[Journal Impact Factor: 2.0]**

12. **J.A. Vaccaro**, "T Violation and the Unidirectionality of Time", *Found. Phys.* **41**, 1569-1596 (2011). (Eprint http://arxiv.org/abs/0911.4528)
    [Journal Impact Factor: 1.2]

13. **J.A. Vaccaro**, "Particle-wave duality: a dichotomy between symmetry and asymmetry", *Proc. Roy. Soc.*, **468**, 1065-1084 (2012). (Eprint http://arxiv.org/abs/1105.0083)
    [2 citations] Ranked A* by ERA 2010 **[Journal Impact Factor: 2.0]**

14. J.A. Vaccaro, “Comment on ‘Operator formalism for the Wigner phase distribution’ ”, J. Mod. Optics **60**, 769-771 (2013). **[Journal Impact Factor: 1.2]**

* 15. S.M. Barnett and **J.A. Vaccaro**, “Beyond Landauer erasure”, Entropy, (accepted 31 October, 2013). (Eprint http://arxiv.org/abs/1310.7821) **[Journal Impact Factor: 1.3]**

Refereed Conference Proceedings

* 16. **J.A. Vaccaro** and S.M. Barnett, “The Cost of Erasing Information”, AIP Conf. Proc. **1110**, 37 (2009).

17. G.A. White, **J.A. Vaccaro** and H.M. Wiseman, “The Consumption of Reference Resources”, AIP Conf. Proc. **1110**, 79 (2009).

* 18. **J.A. Vaccaro**, “Unidirectionality of time induced by T violation”, J. Phys.: Conf. Ser. **306**, 012057 (2011). http://dx.doi.org/10.1088/1742-6596/306/1/012057

Other - International Conferences and Workshops

19. H.M. Wiseman and **J.A.Vaccaro**, “The entanglement of indistinguishable particles shared between two parties” in *A*dvances In Quantum Information Processing: From Theory To Experiment, Erice, Sicily, Italy, 15-22 March 2003 (**Talk**).

20. A.D. Greentree, D. Richards, **J.A. Vaccaro**, A.V. Durrant, S. de Echaniz, D. Segal, J. Marangos, “Lossless intensity-dependent dispersion and group velocity in coherently prepared multi-state atoms using EIT” in *E*uropean Quantum Electronics Conference 2003, Munich, Germany, 23-27 June, 2003 (**Talk**).

21. H.M. Wiseman, S.D. Bartlett and **J.A. Vaccaro**, “Ferreting out the fluffy bunnies: entanglement constrained by generalized super-selection rules” in *1*6th International Conference on Laser Spectroscopy, Palm Cove, Queensland, Australia, 13-18 July 2003 (**Talk**).

22. Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka and M. Sasaki, “Implementing quantum noiseless coding using linear optics” in *E*RATO Conference on Quantum Information Science, Kyoto, Japan, 4-6 September, 2003 (**Talk**).

23. **J.A. Vaccaro**, H.M. Wiseman and F. Anselmi, “Entanglement of identical particles and reference phase uncertainty”, Workshop on *Non-locality of Quantum Mechanics and Statistical Inference*, Kyoto Sangyo University, Kyoto, 8-9 September, 2003. (**Invited Speaker**).

24. **J.A. Vaccaro**, Y. Mitsumori, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, “Quantum data compression”, in *S*tochastic Algorithms: Foundations and Applications Hatfield, September, 2003. (**Invited Speaker**).

25. H.M. Wiseman and **J.A. Vaccaro**, “The entanglement of indistinguishable particles shared between two parties”, Quantum Interference, Correlations and Technology Network Meeting, Abingdon UK, 11-13 July 2003. (**Invited Speaker**).

26. Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka and M. Sasaki, “Implementing quantum noiseless coding using linear optics”, International Conference on Quantum Information, Oxford, 13-17 July 2003 (**Talk**).

27. Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka and M. Sasaki, “Implementing quantum noiseless coding, or how to QuWinZip”, Quantum Circuits Network Workshop: Circuits for Quantum Computation, Southampton UK, 27 July 2003. (**Invited Speaker**).

28. **J.A. Vaccaro**, “Complementarity of nonlocal resources: accessible entanglement versus shared reference frame”, Workshop on Reference Frames and Superselection Rules in Quantum Information Theory, Perimeter Institute for Theoretical Physics, Waterloo Canada, 12-16 July 2004. (**Invited Speaker**).

29. **J.A. Vaccaro**, A. Chefles and J. Spring, “Secure quantum protocols for voting”, Quantum Information and Quantum Control Conference, Fields Institute, Toronto, 19-23 July 2004 (**Talk**).

30. **J.A. Vaccaro**, F. Anselmi, and H.M. Wiseman, “Quantifying shared reference frames” The Seventh International Conference on Quantum Communication, Measurement and Computing QCMC’04, Glasgow UK, 25-29 July 2004 (**Talk**).

31. **J.A. Vaccaro**, F. Anselmi, H.M. Wiseman and K. Jacobs, “Complementarity between work, entanglement and reference ability under arbitrary superselection rules”, 9th International Conference on Squeezed States and Uncertainty Relations ICSSUR’2005, Besançon, France 2-6 May 2005. (**Invited Speaker**).

32. H.W. Wiseman, A.C. Doherty and **J.A. Vaccaro**, “The preferred Ensemble Fact with Applications to Quantum Feedback Control”, 16th National Congress 2005 Australian Institute of Physics Congress, The Australian National University, Canberra, Australia, 31 January - 4 February, 2005 (**Talk**).

33. **J.A. Vaccaro**, “Group theoretic formulation of complementarity”, 8th International Conference on Quantum Communication, Measurement and Computing, Tsukuba International Congress Center, Tsukuba, Japan, 28 November - 3 December, 2006 (**Talk**).

34. G. White and **J.A. Vaccaro**, “Optimal reference ancillas for maximising accessible entanglement of identical particles”, 17th National Congress 2005 Australian Institute of Physics Congress, Brisbane, Australia, 3-8 December 2006 (**Poster**).

35. **J.A. Vaccaro**, “An Information Theoretic Formulation of Complementarity”, International Workshop on Quantum Algorithms and Applications, Blue Mountains, Australia, May 27 - June 2, 2007 (**Invited Speaker**).

36. **J.A. Vaccaro**, S.M. Barnett and D.T. Pegg, “Flow of Time in a Quantum Mechanical World”, Perimeter Institute-Australia Foundations (PIAF) Workshop in Quantum Foundations, Sydney, Australia, 1-3 February 2008 (**Talk**).

* 37. **J.A. Vaccaro** and S.M. Barnett, “The Cost of Erasing Information”, 9th International Conference on Quantum Communication, Measurement and Computing, University of Calgary, Canada, August 19 - 24, 2008 (**Poster**).

38. G.A. White, **J.A. Vaccaro** and H.M. Wiseman, “The Consumption of Reference Resources”, 9th International Conference on Quantum Communication, Measurement and Computing, University of Calgary, Canada, August 19 - 24, 2008 (**Poster**).

39. **J.A. Vaccaro**, “Origin of the anthropocentric flow of time?”, The Clock and the Quantum: Time in Quantum Foundations, Perimeter Institute, Waterloo, Canada, September 28 - October 2, 2008 (**Talk**).

* 40. **J.A. Vaccaro** and S.M. Barnett, “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 (**Invited Speaker**).

41. **J.A. Vaccaro**, “Universe as a quantum computer: algorithm for the shortest path through time”, Scottish Quantum Information Research Network Workshop QUISCO, Strathclyde University, Glasgow, UK, 19th April 2010 (**Invited Speaker**).

* 42. **J.A. Vaccaro**, “Unidirectionality of time induced by T violation”, Fifth International Workshop on Decoherence, Information, Complexity and Entropy DICE2010, Castiglioncello, Tuscany, Italy, 13-17 September 2010 (**Talk**).

* 43. **J.A. Vaccaro**, “Erasure of information under conservation laws”, Quantum Information and Foundations of Thermodynamics, ETH Zurich, Switzerland, 9-12 August 2011 (**Invited Speaker**).

Part 2 Details of ARC grants in the last 10 years

No ARC grants.

G11.3. Ten career-best publications

(Please attach a PDF with a list of your ten career-best publications (4 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

A/Prof Joan A Vaccaro

10 Best Publications

Asterisked publications are relevant to the current proposal. Journal Impact Factors are from Thomson Reuters Journal Citation Reports. Citations are from ISI Web of Science Cited Reference Search.

1. H.M. Wiseman and **J.A. Vaccaro**, "The entanglement of indistinguishable particles shared between two parties", *Phys. Rev. Lett.* **91**, 097902 (2003).
   [103 citations] **[Journal Impact Factor: 7.9]**
   Shows that entanglement is reduced in the presence of superselection rules. Superselection rules and their associated references are central to understanding the cost of quantum entanglement and other nonlocal resources.

2. S.F. Huelga, **J.A. Vaccaro**, A. Chefles and M.B. Plenio, "Quantum Remote Control - Teleportation of Unitary Operations", *Phys. Rev. A*, **63** 042303 (2001).
   [95 citations] **[Journal Impact Factor: 3.0]**
   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.

3. **J.A. Vaccaro** and D.T. Pegg, "Phase properties of squeezed states of light", *Opt. Comm.* **70**, 529-534 (1989).
   [90 citations] **[Journal Impact Factor: 1.4]**
   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.

4. S.M. Barnett, K. Burnett and **J.A. Vaccaro**, "Why a condensate can be thought of as having a definite phase", *Research Journal of the National Institute of Standards* **101**, 593-600 (1996).
   [54 citations]
   This work shows how the phase of a Bose-Einstein condensate arises from the robustness of coherent-like states. Robust states underlie the emergence of classicality in open quantum systems.

5. **J.A. Vaccaro**, "Number-phase Wigner function on Fock space", *Phys. Rev. A* **52**, 3474-3488 (1995).
   [46 citations] **[Journal Impact Factor: 3.0]**
   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.

6. **J.A. Vaccaro**, J. Spring and A. Chefles, "Quantum protocols for anonymous voting and surveying", *Phys. Rev. A* **75**, 012333 (2007).
   [30 citations] **[Journal Impact Factor: 3.0]**
   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.

7. Y. Mitsumori, **J.A. Vaccaro**, S.M. Barnett, E. Andersson, A. Hasegawa, M. Takeoka, and M. Sasaki, "Experimental demonstration of quantum source coding", *Phys. Rev. Lett.* **91**, 217902 (2003).
   [12 citations] **[Journal Impact Factor: 7.9]**
   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, "Information erasure without an energy cost", *Proc. R. Soc. A* **467**, 1770-1778 (2011). (Eprint http://arxiv.org/abs/1004.5330)
   Ranked A* by ERA 2010 **[Journal Impact Factor: 2.0]**
   Overturns the accepted view that the erasure of information incurs an energy cost (Landauer's principle). It is a cornerstone publication for the foundations of thermodynamics.

9. **J.A. Vaccaro**, "T Violation and the Unidirectionality of Time", *Found. Phys.* **41**, 1569-1596 (2011). (Eprint http://arxiv.org/abs/0911.4528) **[Journal Impact Factor: 1.2]**

   Shows that processes (like kaon decay) that violate time-reversal invariance underlie a mechanism that is responsible for the fixed direction of time. This work overhauls our understanding of time.

10. **J.A. Vaccaro**, "Particle-wave duality: a dichotomy between symmetry and asymmetry", *Proc. Roy. Soc.*, **468**, 1065-1084 (2012). (Eprint http://arxiv.org/abs/1105.0083)
    [2 citations] Ranked A* by ERA 2010 **[Journal Impact Factor: 2.0]**

    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.

G11.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

1. OTHER RESEARCH OUTPUTS

A. PATENTS

Patent number: GB 2400252 A
M. Sasaki, Y. Mitsumori, A. Hasegawa, M. Takeoka, J.A. Vaccaro, S.M. Barnett, and E. Andersson, "Optical apparatus for implementing Schumacher's quantum data compression".
Awarded 6 April 2005.

Patent number: Japan 3858067
M. Sasaki, Y. Mitsumori, A. Hasegawa, M. Takeoka, J.A. Vaccaro, S.M. Barnett, and E. Andersson, "Quantum source coding apparatus and quantum information communication system".
Awarded 29 September 2006.

Patent number: US 07403713 B2
M. Sasaki, Y. Mitsumori, A. Hasegawa, M. Takeoka, J.A. Vaccaro, S.M. Barnett, and E. Andersson, "Quantum source coding apparatus and quantum information communication system".
Awarded 22 July 2008.

B. GRANTS

In the UK:
GBP11,034, EPSRC Grant GR/M15736 "Giant Kerr nonlinearities and single-photon cavity control in laser-cooled rubidium", 24 August 1998-03 January 2002.

GBP2,000, British Council, Japan Travel Grant, 25 August-19 September 2003.

GBP21,000, Leverhulme Trust Research Fellowship RF/2004/0395, 1 September 2004-31 August 2006.

GBP2,500, British Council, Japan Travel Grant, 14-18 February 2005.

GBP546, Royal Society, London, Travel Grant, 2-6 May 2005.

In Australia:
$9,859, Griffith University Research Project "Quantum Physics and Information" January 2009 - December 2010.

$171,707, Lockheed Martin Coporation, "Information Erasure and Coherence in Quantum Dots", August 2013 - July 2014.

C. INTERNATIONAL REVIEWER FOR GOVERNMENT RESEARCH AGENCY

In August 2003 I was invited to be a member of the External Review Committee of the Basic and Advanced Research Division of the Communication Research Laboratory, JST, Japan. The review was a mid-term (3 year) international review of a government funded research organisation with an annual budget of over $24M. I examined the report prepared by the Division, toured the research facilities in Tokyo, and attended a one-day review in which the program managers were interviewed by the Committee. I subsequently prepared a written report on the research achievements over the previous 3 years and assessed the plans for the next 3 years. The organisation was renamed National Institute for Information and Communications Technology in 2004.

D. INVITATIONS TO EXAMINE THESES AND ASSESS COMPETITIVE GRANT APPLICATIONS

I have examined 7 PhD theses as an external examiner for
-- Imperial College, London, UK (2),

-- University of Strathclyde, Glasgow, UK (1),
-- University College, London, UK (1) and
-- Griffith University, Australia (1)
-- Macquarie University, Australia (1)
-- University of Sydney (1)
and 2 Masters thesis for
-- University of Melbourne (1)
-- University of Western Australia (1).

I was elected to the Peer Review College of the Engineering and Physical Sciences Research Council in the UK for 2002-2005 during which I reviewed 14 grant and fellowship applications.

E. REFEREE FOR INTERNATIONAL JOURNALS

I regularly act as referee for
-- Physical Review Letters
-- Physical Review A
-- Journal of Physics A
-- Journal of Physics B
-- Physics Letters A
-- Journal of Modern Optics
-- Optics Communications
-- European Physical Journal D
-- New Journal of Physics

2. EVIDENCE OF THE QUALITY OF MY RESEARCH

A. QUALITY OF JOURNALS

Percentage of publications in journals ranked according to the 2010 ERA evaluation:
13% in A* ranked journals
44% in A
42% in B
1% in C

B. CITATION STATISTICS: ISI Web of Science (20/1/2012)

H-index: 21
Total number of citations: 1272
Thompson's ResearcherID: B-9634-2008 (http://www.researcherid.com/rid/B-9634-2008)

C. REVIEW OF MY RESEARCH BY THE New Scientist MAGAZINE

I presented preliminary results of my work on the physical nature of time at the conference "The Clock and the Quantum: Time in Quantum Foundations", Perimeter Institute, Waterloo, Canada in September 2008 (publication number 12 in F14.2). This talk was reviewed in an in-depth 4 page article in the New Scientist magazine,

- M. Brooks, "What makes the universe tick?", New Scientist, 22 Nov 2008, p 32-35.
- http://www.newscientist.com/article/mg20026831.500-what-makes-the-universe-tick.html

D. REVIEW OF MY RESEARCH ONLINE AT PhysOrg.com

My paper on the erasure of information (publication number 5 in F14.2) has been reviewed by the online magazine PhysOrg.com. Excerpt of the feature review:

"Until now, scientists have thought that the process of erasing information requires energy. But a new study shows that, theoretically, information can be erased without using any energy at all. Instead, the cost of erasure can be paid in terms of another conserved quantity, such as spin angular momentum..."
- L. Zyga, "Scientists show how to erase information without using energy", PhysOrg.com, 25 January 2011
- http://www.physorg.com/news/2011-01-scientists-erase-energy.html

E. REVIEWS OF MY BOOK "The Quantum Phase Operator: A Review"

My book (publication number 1 in F14.2) on the quantum phase operator has received the following reviews:

"If you want to learn how to define a Hermitian phase operator without getting into a whole lot of trouble you should read the first six chapters...no one professing expertise in modern quantum optics can afford not to read it."
- G.J. Milburn, Australian Physics 46, 86 (2009).

"Since the commentary introductions to the chapters are well readable, this book can well serve as a textbook for people who have some fundamental knowledge in quantum optics"
- K.-E. Hellwig, Zentralblatt Math, Zbl 1155.81006 (2010).
- http://www.zentralblatt-math.org/zmath/en/search/?q=an:1155.81006

F. INVITED TALKS AT INTERNATIONAL CONFERENCES AND WORKSHOPS (last 10 years)
Workshop on Non-locality of Quantum Mechanics and Statistical Inference, Kyoto Japan, September 2003.
Workshop on Reference Frames and Superselection Rules in Quantum Info. Theory, Perimeter Institute, Waterloo Canada, July 2004.
9th International Conference on Squeezed States and Uncertainty Relations, Besancon France, 2005.
International Workshop on Quantum Algorithms and Applications, Blue Mountains, May 2007
8th Asian International Seminar on Atomic and Molecular Physics, Perth, November 2008
Scottish Quantum Information Research Network Workshop, Glasgow UK, April 2010
Quantum Information and Foundations of Thermodynamics, Zurich Switzerland, August 2011
World Congress on Nano Science & Technologies 2012, Qingdao, China, October 2012.
Relativistic Quantum Information 6 Workshop, Customs House, Brisbane, 28-30 November 2012.
Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT13), Prague, Czech Republic, July 2013.

G11.5. A statement on your most significant contributions to this research field of this Proposal

(Write a maximum of 3750 characters (approx 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

The demonstration of the principle of erasing information without a cost in energy published as

J.A. Vaccaro and S.M. Barnett, "The Cost of Erasing Information", AIP Conf. Proc. 1110, 37-40 (2009).

J.A. Vaccaro and S.M. Barnett, "Information erasure without an energy cost", Proc. R. Soc. A 467, 1770-1778 (2011),
http://arxiv.org/abs/1004.5330

S.M Barnett and J.A. Vaccaro, "Beyond Landauer erasure", Entropy (in press 2013),
http://arxiv.org/abs/1310.7821

These results underpin all the research proposed in this project.

I was the sole theorist in a collaboration (between Imperial College, London, The Open University, Milton Keynes, UK and the University of Hertfordshire, Hatfield, UK) that investigated both experimentally and theoretically Electromagnetically Induced Transparency (EIT) in a gas of rubidium atoms confined in a Magneto-Optical Trap (MOT) over the period 1995-2003.

My role was to guide the experimental investigation by providing preliminary models of what we might expect to observe for ranges of experimental parameters (laser field strengths, gas densities, detunings etc) and then to provide the interpretation of the actual experimental results. For this I modelled the dynamics of the gas undergoing pump-probe interactions with laser fields in many different configurations such as
* scanning optical frequencies,
* varying number of fields,
* off resonant and on resonant interactions,
* varying optical polarizations,
* varying spatial geometries,
* varying hyperfine transitions,
* varying Zeeman sublevels,
* modelling propagation effects in the gas,

* steady states and
* transients and time evolutions etc.
I solved the corresponding master equations numerically using FORTRAN and the NAG libraries in a UNIX environment on DEC Alpha minicomputers.

This background in computational physics is more than adequate for modelling spin reservoirs in semiconductor heterostructures in Aim 1 of the present project.

The significant papers of this collaboration are as follows:

H.X. Chen, A.V. Durrant, J.P. Marangos and J.A. Vaccaro, "Observation of transient electromagnetically induced transparency in a rubidium lambda system", Phys. Rev. A, 58 1545-1548 (1998).
[citations 31]

A.V. Durrant, H.X. Chen, S.A. Hopkins and J.A. Vaccaro, "Zeeman-coherence-induced transparency and gain without inversion in laser-cooled rubidium", Optics Commun., 151 135-146 (1998).
[citations 22]

A.D. Greentree, J.A. Vaccaro, S.R. de Echaniz, A.V. Durrant, J. Marangos, "Prospects for photon blockade in four level systems in the N configuration with more than one atom", Journal of Optics B 2, 252-259 (2000).
[citations 23]

S.R. de Echaniz, A.D. Greentree, A.V. Durrant, D. Segal, J. Marangos and J.A. Vaccaro, "Observations of a doubly driven V system probed to a fourth level in laser-cooled rubidium", Phys. Rev. A 64, 3812 (2001).
[citations 24]

S.R. de Echaniz, A.D. Greentree, A.V. Durrant, D. Segal, J. Marangos and J.A. Vaccaro, "Observation of transient gain without population inversion in laser-cooled rubidium lambda systems" Phys. Rev. A, 64 055801 (2001).
[citations 12]

A.D. Greentree, T.B. Smith, S.R. de Echaniz, A.V. Durrant, D. Segal, J. Marangos and J.A. Vaccaro, "Resonant and off-resonant transients in electromagnetically induced transparency: turn-on and turn-off dynamics", Phys. Rev. A 65, 053802 (2002).
[citations 24]

A.D. Greentree, D. Richards, J. A. Vaccaro, A. V. Durrant, S. R. de Echaniz, D. M. Segal, J. P. Marangos, "Intensity-dependent dispersion under conditions of electromagnetically induced transparency in coherently prepared multi-state atoms", Phys. Rev. A 67, 023818 (2002).
[citations 26]

PART G - Personnel (Dr Luke Uribarri)

G1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Doctor

Family Name

Uribarri

First Name

Luke

Second Name

Alexander

Person identifier

54436445

Role

Partner Investigator

G2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

Unit 3360 Box 105

Locality

DPO

State

AA

Postcode

34035

Country

United States of America

G3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to ARC College or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

G4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 July 2014.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

G5. Are you an Indigenous Participant?

Indigenous Participant

No

G6. PhD Qualification

Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

28/09/2008

G7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	2008	Aerospace Engineering	Princeton University, USA
2	BS	2003	Aerospace Engineering	University of Southern California

	Country
1	United States of America

	Country
2	United States of America

G8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Deputy to the Chief Scientist in matters of program management, technical advisory, and technology transfer	Lockheed Martin (US)	Corporate Engineering and Technology	2008

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes

G9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 July 2014 and beyond; for PIs it will generally be their main employer as at 1 July 2014).)

Organisation Name

Lockheed Martin (US)

Type of Affiliation

Employee

G10. Time commitment (%FTE) to this Project

10

G11. Research Opportunity and Performance Evidence (ROPE)

G11.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i) Number of years since graduating with highest educational qualification
I graduated with a PhD in mechanical and aerospace engineering from Princeton University in 2008, five years ago. Prior to that I completed a Masters in the same area in 2005 also at Princeton, and completed a Bachelor of Science Summa Cum Laude in aerospace engineering at University of Southern California in 2003.

(ii) Research opportunities in the context of employment situation
I have been employed in Lockheed Martin's Advanced Developed Programs "Skunk Works" since graduating in 2008, first as a Senior Aeronautical Engineer and later as a Project Manager and Deputy to the Chief Scientist in the Chief Scientist's Office. This has provided excellent – even unique – opportunities for research, research management, and technological development. Skunk Works exists to create breakthrough aeronautical technologies and landmark aircraft, and has been responsible for developing 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.

(iii) Classification of current appointment
I am currently a Senior Aeronautical Engineer and Deputy to the Chief Scientist at Lockheed Martin, and hold an Adjunct Professorship at George Washington University. Currently and over the past five years, my

responsibilities are split approximately 35/35/20/10 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.

(iv) Career interruptions for childbirth, carer's responsibility, misadventure, or debilitating illness
I have had no significant career interruptions from childbirth, carer's responsibility, misadventure, or debilitating illness.

(v) Available research mentoring and research facilities
Lockheed Martin is one of the world's largest technology companies, with turnover of $50 billion dollars in 2012 comparable to Google. It is also the world's largest defence contractor. Skunk Works is the premier research arm of Lockheed, with the freedom to undertake blue-sky research as well as practical applications. Skunk Works has 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 also sponsors external development course. I have benefited from this, attending courses in Capture Management, and Customer Value Conversations. Being an Adjunct Professor at George Washington University I also have access to academic research facilities and mentoring.

(vi) Other aspects of career or opportunities for research relevant to assessment
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.

G11.2. Recent significant publications and ARC grants (since 2003)

(Please attach a PDF with a list of your recent significant publications and ARC grants most relevant to this Proposal (10 Pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

G11.2. Recent significant publications

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.

(1) List of publications since 2003

(i) *Scholarly books* – not applicable.

(ii) *Scholarly book chapters* – not applicable.

(iii) *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).

(iv) *Refereed conference papers*

(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.

(v) ***Other publications***

* (6) 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).

(7) **Luke A. Uribarri**. *Onset voltage hash and anode spots in quasi-steady magnetoplasmadynamic thrusters*. PhD Dissertation, Princeton University, 2008.

(2) ARC grants awarded in the past 10 years

I have no ARC research grants to report.

G11.3. Ten career-best publications

(Please attach a PDF with a list of your ten career-best publications (4 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

G11.3. Ten career-best publications

As discussed in **Section G11.2**, 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. Note: **Section G11.2** 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. It also includes a list of academic publications.

G11.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

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 twelve 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
- Hypersonic flight, and
- Low-cost space launch systems

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.

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

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---for which the need for high-energy-density storage technologies is acute. The specific area of my PhD was propulsion systems to launch 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 Lockheed; all of whom I have worked closely with.

Academic Experience

Since 2011, whist maintaining a full-time position at Lockheed, I have been an Adjunct Professor at George Washington University, where I teach graduate-level coursework in the Aerospace and Mechanical Engineering department, and counsel 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.

G11.5. A statement on your most significant contributions to this research field of this Proposal

(Write a maximum of 3750 characters (approx 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

My role within this Linkage Project will be to provide leadership and technical capacity in the areas of research development, commercialisation, as well as strong established links and communication channels within the technology and defence industries. I have ten years of research and development experience, half of this within industry, and half in academia. Over that time I have developed extensive industrial and academic experience in program and capture management, customer interfacing, strategic planning, research management, export policy, technical execution, and product deployment.

*Research development expertise

As a Senior Engineer, Technology Manager, and Deputy to the Chief Scientist at Lockheed Martin, I have deep expertise in conceiving, structuring, and managing projects, and in creating development paths to realize practical devices and applications from conceptual technologies founded in basic science (technology readiness level 0/1). I provide scientific leadership within small teams to achieve program goals for both internal Lockheed and external R&D, and manage research and development portfolios with a total current value of US$6M. I have, further, managed three independent research and development (IR&D) activities to successful conclusions, with values in the range of US$200-500k. The IR&D budget that I oversee in 2013 and 2014 is valued at $2.4M and encompasses eight interrelated university research projects. These projects, activities and portfolios cover a broad range of technological areas, including plasma physics, hypersonics, materials science, alternative energies, nanotechnology, and quantum physics.

This Linkage Project sets out an ambitious program of research and development, taking basic ideas from quantum physics and thermodynamics, and seeking to realise new energy storage applications. One of my key roles is to provide a technical interface between CI Vaccaro's scientific expertise and the needs of industry customers who can make use of the products of her research. Combined with my own background in technology and research development, and access to Lockheed’s wide range of infrastructure, this role that I will play will be crucial to the long-term practical application of the research.

*Established links with technology/defense industries

Access to world leaders in the defense and technology space, and the ability to work closely with them, will be important to maximise the end-user outcomes of this Linkage Project. Over the course of my career I have developed extensive links within the technology and defense industries. I work closely with the US Defense Advanced Research Projects Agency (DARPA), the Air Force Research Laboratory, and NASA; and maintain a Top Secret US Department of Defense security clearance affording access to national security, counterterrorism, counterintelligence, and other highly sensitive data. I have been employed by Boeing to undertake a market analysis of NASA’s space science portfolio; and by HSW Engineering, an integrated earth science and engineering firm. I have also previously worked for the Institute for Defense Analyses, which provides the US Federal Government with objective analyses of national security issues, particularly those requiring scientific and technical expertise, and conducts related research on other national challenges, where I interfaced directly with the Departments of Defense, State, Commerce, and the Senate

Armed Services Committee.

PART G - Personnel (A/Prof Kimberley Hall)

G1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Associate Professor

Family Name

Hall

First Name

Kimberley

Person identifier

18538567

Role

Partner Investigator

G2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

Department of Physics and Atmospheric Science

Postal Address Line 2

Dalhousie University

Locality

Halifax

State

Nova Scotia

Postcode

B3H 4R2

Country

Canada

G3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to ARC College or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

G4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 July 2014.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

G5. Are you an Indigenous Participant?

Indigenous Participant

No

G6. PhD Qualification

Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

08/06/2002

G7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1				
2				

	Country
1	

	Country
2	

G8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Associate Professor	Dalhousie University, Canada	Physics and Atmospheric Science	2007
2	Assistant Professor	Dalhousie University, Canada	Physics and Atmospheric Science	2004
3	Postdoctoral Researcher	University of Iowa	Physics and Astronomy	2002

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes
2	Permanent	Full Time	No
3	Contract	Full Time	No

G9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 July 2014 and beyond; for PIs it will generally be their main employer as at 1 July 2014).)

Organisation Name

Dalhousie University, Canada

Type of Affiliation

Employee

G10. Time commitment (%FTE) to this Project

25

G11. Research Opportunity and Performance Evidence (ROPE)

G11.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i) The number of years since PhD awarded

I received my PhD in physics 11 years ago from the University of Toronto.

(ii) Research opportunities

I was a full time postdoctoral researcher from 2002 to 2004 in the Department of Physics and Astronomy and Optical Science and Technology Center, The University of Iowa.

My career as a research group leader began in 2004, when I was appointed to a full time faculty member in the Department of Physics and Atmospheric Science at Dalhousie University.

(iii) Academic profile

From 2002 to 2004 my appointment was approximately 100% research.
From 2004 my profile has been 20% teaching : 10% administration : 70% research

(iv) Career interruptions
I have had no interruptions.

(v) Research mentoring and research facilities available

In 2007 Dalhousie was ranked number one outside the US for research environment in The Scientist's "Best Places to Work in Academia". According to a survey conducted by The Scientist, Dalhousie was the best non-commercial scientific institute in which to work in Canada.

The research facilities available for this project are the Dalhousie Ultrafast Quantum Control Laboratories of which I am Director. It houses a pair of state-of-the-art femtosecond laser laboratories equipped with both OPO and OPA tunable laser sources, in addition to a superconducting 7 Telsa optical cryostat, and microscopy cryostat with cryogenic sample nanopositioning capability.

(vi) Any other aspects

When I arrived at Dalhousie University 9 years ago there was no experimental work performed here on semiconductor physics. I have built the Dalhousie Ultrafast Quantum Control Laboratories from a total of approximately $3.9 million in funding from the Lockheed Martin Corporation and NSERC Discovery projects.

I have made pioneering contributions to the fields of Spintronics and Solid State Quantum Computing (including a US patent on a Spin Transistor) and published 37 journal articles and given 61 invited talks.

G11.2. Recent significant publications and ARC grants (since 2003)

(Please attach a PDF with a list of your recent significant publications and ARC grants most relevant to this Proposal (10 Pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

G11.2 Recent significant publications and ARC grants (Hall, Kimberley C.)

(1) A List of Recent Publications Most Relevant to This proposal:

Refereed Journal Articles:

1. D. Webber, T. de Boer, M. Yildirim S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. K. Furdyna, and K. C. Hall, ***Measurement of Coherence Decay in GaMnAs using Femtosecond Four-Wave Mixing***, J. Vis. Exp. (Invited), Accepted Aug 27, 2013, in press (2013).

*2. A. Gamouras, R. Mathew, S. Freisem, D. G. Deppe, and K. C. Hall, ***Simultaneous Deterministic Control of Distant Qubits in Two Semiconductor Quantum Dots***, Nano Lett. 13, 4666 (2013).

*3. M. Yildirim, S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. K. Furdyna, and K. C. Hall, ***Interband Dephasing and Photon Echo Response in GaMnAs***, Appl. Phys. Lett. 101, 062403 (2012).

*4. A. Gamouras, R. Mathew, and K. C. Hall, ***Optically Engineered Ultrafast Pulses for Controlled Rotations of Exciton Qubits in Semiconductor Quantum Dots***, J. Appl. Phys. 112, 014313 (2012).

5. T. De Boer, S. March, V. Novak, and K. C. Hall, ***Observation of a Blue Shift in the Optical Response at the Fundamental Band Gap in GaMnAs***, Phys. Rev. B 85, 033202 (2012).

*6. Reuble Mathew, Craig E. Pryor, Michael E. Flatté, and Kimberley C. Hall, ***Optimal quantum control for conditional rotation of exciton qubits in semiconductor quantum dots***, Phys. Rev. B 84, 205322 (2011).

*7. M. Yildirim, S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. K. Furdyna, and K. C. Hall, ***Electronic structure of GaMnAs probed by four-wave mixing spectroscopy***, Phys. Rev. B 84, 121202(R) (2011).

8. J. P. Zahn, A. Gamouras, S. March, X. Liu, J. K. Furdyna, and K. C. Hall, ***Ultrafast Studies of Carrier and Magnetization Dynamics in GaMnAs***, J. Appl. Phys. 107, 033908 (2010).

9. K. C. Hall, J. P. Zahn, A. Gamouras, S. March, J. L. Robb, X. Liu, and J. K. Furdyna, ***Ultrafast optical control of coercivity in GaMnAs***, Appl. Phys. Lett. 93, 032504 (2008).

10. J. L. Robb, Y. Chen, A. Timmons, O. B. Shchekin, D. G. Deppe, and K. C. Hall, ***Time-resolved Faraday rotation measurements of spin relaxation in InGaAs/GaAs quantum dots: Role of excess energy,*** Appl. Phys. Lett. 90, 153118 (2007).

11. K. C. Hall, E. J. Koerperick, T. F. Boggess, O. B. Shchekin, and D. G. Deppe, ***Hole Spin Relaxation in neutral InGaAs quantum dots: Decay to dark states***, Appl. Phys. Lett. 90, 053109 (2007); *Selected for:* Virtual Journal of Nanoscale Science & Technology, February (2007).

12. K. C. Hall, ***High-Performance Spin FET Using Gate-Controlled Spin Relaxation***, Physics in Canada 63, 79-84 (2007).

13. K. C. Hall and M. E. Flatte, ***Performance of a spin-based insulated gate field effect transistor***, Appl. Phys. Lett. 88, 162503 (2006).

14. J. Hicks, K. Gündoğdu, A. N. Kocbay, K. C. Hall, T. F. Boggess, K. Holabird, A. Hunter, and J. J. Zinck, ***Bias-Dependent spin relaxation in a [110]-InAs/AlSb 2DES***, Physica E 34, 371 (2006).

15. K. C. Hall, K. Gundogdu, J. L. Hicks, A. N. Kocbay, M. E. Flatte, T. F. Boggess, K. Holabird, A. Hunter, D. H. Chow, J. J. Zinck, ***Room-temperature electric-field controlled spin dynamics in (110) InAs quantum wells,*** Appl. Phys. Lett. 86 (20): Art. No. 202114, 3 pages (2005).

16. K. Gundogdu, K. C. Hall, E. J. Koerperick, C. E. Pryor, M. E. Flatte, T. F. Boggess, O. B. Shchekin, D. G. Deppe, ***Electron and hole spin dynamics in semiconductor quantum dots,*** Appl. Phys. Lett. 86 (11): Art. No. 113111, 3 pages (2005).

17. J. J. Zinck, D. H. Chow, K. S. Holabird, J. N. Schulman, K. C. Hall, T. F. Boggess, ***Resonant tunneling in (110) oriented interband diodes***, Appl. Phys. Lett. 86 (7): Art. No. 073502, 3 pages (2005).

18. K. Gundogdu, K. C. Hall, T. F. Boggess, D. G. Deppe, O. B. Shchekin, ***Ultrafast electron capture into p-modulation-doped quantum dots,*** Appl. Phys. Lett. 85 (20): 4570-4572 (2004).

19. S. Calvez, J.-M. Hopkins, S. A. Smith, A. H. Clark, R. Macaluso, H. D. Sun, M. D. Dawson, T. Jouhti, M. Pessa, K. Gundogdu, K. C. Hall, T. F. Boggess, ***GaInNAs/GaAs Bragg-mirror-based structures for novel 1.3 μ m device applications***, J. Crystal Growth 268 (3-4): 457-465 (2004).

20. H. D. Sun, R. Macaluso, S. Calvez, G. J. Valentine, D. Burns, M. D. Dawson, K. Gundogdu, K. C. Hall, T. F. Boggess, T. Jouhti, and M. Pessa, ***Effects of rapid thermal annealing on the optical properties of low-loss 1.3 μm GaInNAs/GaAs saturable Bragg reflectors***, J. Appl. Phys. 96 (3): 1418-1424 (2004).

21. K. Gundogdu, K. C. Hall, Thomas F. Boggess, D. G. Deppe, O. B. Shchekin, ***Efficient electron spin detection with positively charged quantum dots***, Appl. Phys. Lett. 84, 2793-2795 (2004).

22. K. C. Hall, K. Gundogdu, E. Altunkaya, W. H. Lau, M. E. Flatte, T. F. Boggess, J. J. Zinck, W. B. Barvosa-Carter, and S. L. Skeith, ***Spin Relaxation in (110) and (001) InAs/GaSb Superlattices***, Phys. Rev. B 68, 115311 (5 pages) (2003).

23. K. C. Hall, W. H. Lau, K. Gundogdu, M. E. Flatte, and T. F. Boggess, ***Non-magnetic semiconductor spin transistor***, Appl. Phys. Lett. 83, 2937-2939 (2003).

Refereed Conference Papers:

24. K. C. Hall, D. Webber, M. Yildirim S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. K. Furdyna, ***Measurement of spin-flip scattering time and photon echo response in GaMnAs***, Proc. SPIE 8813-100, Spintronics VI (Invited) submitted Sept 12 (2013).

25. A. Gamouras, R. Mathew, S. Freisem, D. Deppe, and K. Hall, ***Optimal Two-Qubit Quantum Control in InAs Quantum Dots***, in CLEO: 2013, OSA Technical Digest (Optical Society of America), paper QM4B.8 (2013).

26. R. Mathew, A. Gamouras, K. Hall, M. Flatté, and C. Pryor, ***Optimal quantum control for conditional rotation of exciton qubits in semiconductor quantum dots***, Conference on Lasers and Electro-Optics 2012, OSA Technical Digest (Optical Society of America), paper QM3G.2 (2012).

27. X. Liu, Y. Y. Zhou, E. Harley, L. E. McNeil, J. Wang, J. Qi, Y. Xu, A. Steigerwald, N. Tolk, J. P. Zahn, A. Gamouras, S. March, K. C. Hall, and J. K. Furdyna, ***Spin dynamics and manipulation in GaMnAs alloys***, Ultrafast Phenomena in Semiconductors and Nanostructure Materials XIV, Proc. SPIE 7600 Art. No. 76000T (2010).

28. K. C. Hall, J. P. Zahn, S. March, X. Liu, J. K. Furdyna, ***Ultrafast Coercivity and Magnetization Dynamics in GaMnAs***, 2008 Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference, vol 1-93329-3330 (2008).

29. K. C. Hall, K. Gundogdu, Thomas F. Boggess, O. B. Shchekin, D. G. Deppe, ***Carrier and Spin Dynamics in Charged Quantum Dots*** Proc. of SPIE 5361, 12 pages, 76 (2004).

30. D. G. Deppe, O. B. Shchekin, J. Ahn, C. Cao, K. Gundogdu, K. Hall, L. Zhang, and T. Boggess, ***Modulation characteristics of P-doped quantum dot lasers,*** IEEE LEOS Annual Meeting Conference Proceedings 1, 2116-117 (2003).

Other:

31. United States patent filed by the University of Iowa Technology Transfer Office. Awarded February 17, 2009. US007492022B2/US007719070B2. Title of invention: ***Nonmagnetic Semiconductor Spin Transistor***. Inventors: Kimberley C. Hall (Primary), Wayne H. Lau, Kenan Gundogdu, Michael E. Flatte, Thomas F. Boggess. The invention is a nonmagnetic semiconductor spin transistor, in which low applied voltages and/or magnetic fields are used to control the characteristics of spin-polarized current flow.

(2) Details of ARC grants awarded in the last 10 years:

This co-applicant has never been supported by ARC funding, but has had numerous Canadian research grants and has attracted considerable external support via industrial contracts with US companies.

G11.3. Ten career-best publications

(Please attach a PDF with a list of your ten career-best publications (4 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

G11.3 Ten Career-Best Publications (Hall, Kimberley C.)

*1. A. Gamouras, R. Mathew, S. Freisem, D. G. Deppe, and K. C. Hall, ***Simultaneous Deterministic Control of Distant Qubits in Two Semiconductor Quantum Dots***, Nano Lett. 13, 4666 (2013).

The first application of optimal quantum control to quantum gates involving solid state qubits. General pulse shaping was applied to parallel control of distant solid state qubits in quantum dots.

*2. A. Gamouras, R. Mathew, and K. C. Hall, ***Optically Engineered Ultrafast Pulses for Controlled Rotations of Exciton Qubits in Semiconductor Quantum Dots***, J. Appl. Phys. 112, 014313 (2012).

Pulse shaping was applied to the theoretical optimization of a C-ROT gate involving excitons in quantum dots, with experimental pulse characterization and quantum error analysis.

*3. M. Yildirim, S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. K. Furdyna, and K. C. Hall, ***Electronic structure of GaMnAs probed by four-wave mixing spectroscopy***, Phys. Rev. B 84, 121202(R) (2011).

First application of four-wave mixing spectroscopy to a III-Mn-V diluted magnetic semiconductor, illustrating influence of Mn (s,p)-d hybridization on valence density of states. Cited 7 times.

4. K. C. Hall, J. P. Zahn, A. Gamouras, S. March, J. L. Robb, X. Liu, and J. K. Furdyna, ***Ultrafast optical control of coercivity in GaMnAs***, Appl. Phys. Lett. 93, 032504 (2008).

Demonstration of ultrafast optical control of coercivity in GaMnAs via optical control of carrier-mediated ferromagnetic order. Illustrates applicability of the III-Mn-V class of materials to optically-addressable spin magnetic memory. Cited 16 times.

5. K. C. Hall and M. E. Flatte, ***Performance of a spin-based insulated gate field effect transistor***, Appl. Phys. Lett. 88, 162503 (2006).

Numerical modeling of performance of spin transistor, together with comparison with silicon CMOS, indicating promising scaling behavior and reduced power consumption. Cited 47 times.

6. K. C. Hall, K. Gundogdu, J. L. Hicks, A. N. Kocbay, M. E. Flatte, T. F. Boggess, K. Holabird, A. Hunter, D. H. Chow, J. J. Zinck, ***Room-temperature electric-field controlled spin dynamics in (110) InAs quantum wells,*** Appl. Phys. Lett. 86 (20): Art. No. 202114, 3 pages (2005).

Experimental room temperature demonstration of transistor action of spin FET. Mid-IR pump probe techniques used to demonstrate gate control of electron spin lifetime in (110) quantum wells. Cited 28 times.

7. K. Gundogdu, K. C. Hall, T. F. Boggess, D. G. Deppe, O. B. Shchekin, ***Ultrafast electron capture into p-modulation-doped quantum dots,*** Appl. Phys. Lett. 85 (20): 4570-4572 (2004).

Rapid electron trapping demonstrated in p-doped quantum dots using time-resolved photoluminescence techniques, with important implications for fast modulation speeds in quantum dot lasers. Cited 55 times.

8. K. Gundogdu, K. C. Hall, Thomas F. Boggess, D. G. Deppe, O. B. Shchekin, ***Efficient electron spin detection with positively charged quantum dots***, Appl. Phys. Lett. 84, 2793-2795 (2004).

   Electron spin detection efficiency is shown to be strongly enhanced with p-modulation doping for devices incorporating spin-LED configurations for quantum state readout. Cited 28 times.

9. K. C. Hall, K. Gundogdu, E. Altunkaya, W. H. Lau, M. E. Flatte, T. F. Boggess, J. J. Zinck, W. B. Barvosa-Carter, and S. L. Skeith, ***Spin Relaxation in (110) and (001) InAs/GaSb Superlattices***, Phys. Rev. B 68, 115311 (5 pages) (2003).

   Demonstration of enhanced spin lifetime through elimination of Rashba and interface asymmetry contributions to precessional decay in technologically-relevant InAs/GaSb/AlSb system with high mobility and strong spin-orbit interactions. Cited 36 times.

10. K. C. Hall, W. H. Lau, K. Gundogdu, M. E. Flatte, and T. F. Boggess, ***Non-magnetic semiconductor spin transistor***, Appl. Phys. Lett. 83, 2937-2939 (2003).

    Theoretical proposal for a spin field-effect transistor utilizing gate control of spin relaxation in (110)-oriented quantum wells. Cited 78 times.

G11.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

Contributions to Semiconductor Spintronic Device Innovation
I developed several new spin device concepts early in my career that kicked off my international reputation in the field of Spintronics, work that has had profound impact (US Patent, Hall et al. Appl. Phys. Lett. 83, 2937-2939 (2003), 78 citations; Hall et al. Phys. Rev. B 68, 115311 (2003), 36 citations; J. J. Zinck et al. Appl. Phys. Lett. 86, 073502 (2005); Hall et al. Appl. Phys. Lett. 86, 202114 (2005), 28 citations). In recent work, we achieved the room temperature demonstration of the gate switching mechanism in this spin FET based on control of spin relaxation (Hall et al. Appl. Phys. Lett. 86, 202114 (2005), 28 citations), revealing low-threshold operation, a promising achievement for spintronics. This body of work demonstrates the commitment by our research group to the development of novel semiconductor devices that exploit quantum phenomena.
My more recent theoretical work comparing the performance metrics of this spin FET with state-of-the-art MOSFET technology (Hall and Flatté, Appl. Phys. Lett. 88, 162503 (2006), 47 citations), work that was done fully at Dalhousie University, illustrated a dramatic improvement with regard to power consumption. The work in Hall and Flatté, Appl. Phys. Lett. 88, 162503 (2006) led to an invited talk at Princeton as part of the Electronic Materials and Devices Series. This work was also mentioned prominently by Nobel prize winner Albert Fert during his presentation on "Recent Developments and Perspectives in Spintronics" at the 2008 APS March Meeting, illustrating the importance of this work to the Spintronics field.

Pioneering Contributions to the Understanding of Spin Relaxation in Semiconductors
Our research group has a long track record in the study of charge and spin dynamics in quantum wells and ensembles of semiconductor quantum dots, contributing extensively to the understanding of spin relaxation in semiconductor nanostructures (e.g. Hall et al, Appl. Phys. Lett. 75, 4156 (1999), 36 citations; Hall et al. Phys. Rev. B 68, 115311 (2003), 36 citations; Gundogdu et al. Appl. Phys. Lett. 84, 2793 (2004), 28 citations). In recent work, we have demonstrated voltage control over Rashba-induced precessional spin relaxation (K. C. Hall et al. Appl. Phys. Lett. 86, 202114 (2005), 28 citations). In the study of spin relaxation in semiconductor quantum dots, our group performed the first comparison of electron spin dynamics under conditions of resonant excitation of the quantum dot ground state and excitation in the GaAs barriers (Robb et al, Appl. Phys. Lett. 90, 153118 (2007), 7 citations), a measurement made possible by the tunable OPA laser source in our laboratory at Dalhousie. The measured results showed conclusively that non-equilibrium phonons generated under non-resonant excitation severely degrade the spin relaxation time due to the spin-orbit interaction, accounting for the wide range of reported spin lifetimes published by other groups. The central role of phonons in spin relaxation was also highlighted in Gundogdu et al. Appl. Phys. Lett. 86, 113111 (2005) (19 citations), and in Hall et al., Appl. Phys. Lett. 90, 053109 (2007) (11 citations), where the spin lifetimes of holes and electrons were separately measured for the first time in doped, and charge-neutral quantum dots, respectively.

Optical Control of Ferromagnetic Order for Spintronic Device Innovation
Due to the carrier-mediated nature of ferromagnetism in the III-Mn-V diluted magnetic semiconductors, these materials are of interest for developing optically-addressable magnetic memory elements and magnetic contacts in spin-sensitive semiconductor devices. As a result, the process of optical control of ferromagnetic order in these materials has been studied extensively in recent years. Our research group has made ground-breaking contributions in this area, including the first demonstration of carrier-induced enhancement of the coercive field in a III-Mn-V system (K. C. Hall et al., Appl. Phys. Lett. 93, 032504 (2008)) and the first comprehensive study of femtosecond demagnetization in GaMnAs (J. P. Zahn et al., J. Appl. Phys. 107, 033908 (2010)). This work has already had strong impact, with 20 citations, including work by Th. Rasing's group, in which they have extended it to single picojoule pulse switching of magnetization. This lays the ground work for the development of nonthermal memory and associated spintronic devices using this class of materials.

Selected Invited Talks:
1. K. C. Hall, M. Yildirim, S. March, R. Mathew, A. Gamouras, X. Liu, M. Dobrowolska, J. Furdyna, Observation of a Photon Echo and Measurement of Interband Dephasing in GaMnAs, SPIE Optics and Photonics 2013, San Diego, CA, August 2013.

2. K. C. Hall, Ultrafast Control of Exciton Qubits in Semiconductor Quantum Dots, CSSTC 2013: The 16th Canadian Semiconductor Science and Technology Conference, Thunder Bay, Ontario, Canada, August 2013.

3. K. C. Hall, Optimal Quantum Control of Solid State Qubits in Semiconductor Quantum Dots, Photonics North 2013, Ottawa, Ontario, Canada, June 2013.

4. K. C. Hall, A. Gamouras, R. Mathew, D. G. Deppe, C. Pryor, and M. E. Flatte, Optically Engineered Ultrafast Pulses for Controlled Rotations of Excitons in Semiconductor Quantum Dots, 2012 Ultrafast Pulse Shaping Workshop, Michigan State University, Lansing, Michigan, United States, August 2012.

5. K. C. Hall, M. Yildirim, T. De Boer, S. March, A. Gamouras, R. Mathew, X. Liu, J. K. Furdyna, and V. Novak Nonlinear Optical Response of GaMnAs, 2nd Advanced Workshop on Spin and Charge Properties of Low Dimensional Systems, Brasov, Romania, July 2011.

6. K. C. Hall, M. Yildirim, T. De Boer, S. March, A. Gamouras, R. Mathew, X. Liu, and J. K. Furdyna, Ultrafast Carrier Response in GaMnAs, CAP Congress 2011, St. John's, Newfoundland, June 2011.

7. K. C. Hall, M. Yildirim, T. De Boer, S. March, A. Gamouras, R. Mathew, X. Liu, and J. K. Furdyna, Coherent and Incoherent Carrier Response in GaMnAs, Magnetic North II, St. John's, June 2011.

8. K. C. Hall, Ultrafast Control of Spin Dynamics for Applications in Semiconductor Spintronics, Lockheed Martin Skunk Works, Palmdale, California, hosted by Charles Chase, February 2011.

9. K. C. Hall, J. P. Zahn, A. Gamouras, S. March, M. Yildirim, T. De Boer, R. Mathew, X. Liu, and J. K. Furdyna, Ultrafast Control of Ferromagnetic Order in GaMnAs, Nanomagnetism et Spintronics, 23rd Centre Jacques Cartier Meeting, Grenoble, France, November 2010.

10. K. C. Hall, Spin Electro-Optics, Device Research Conference 2010, Notre Dame, Indiana, June 2010.

11. K. C. Hall, Quantum Computing with Semiconductor Quantum Dots, D-Wave Systems, March 2010.

12. K. C. Hall, Quantum Control of Charge and Spin Qubits Using Engineered Optical Pulses, Department of Chemistry, Princeton University, Hosted by Prof. H. Rabitz, Princeton, New Jersey, September 2009.

13. K. C. Hall, Ultrafast Studies of Charge and Spin Dynamics in Semiconductor Nanostructures, ICTP Advanced Workshop: Spin and Charge Properties of Low Dimensional Systems, Sibiu, July 2009.

14. K. C. Hall, Topological Quantum Computing with Semiconductor Quantum Dots, 3rd Quantum Works Annual General Meeting, Montreal, June 2008.

G11.5. A statement on your most significant contributions to this research field of this Proposal

(Write a maximum of 3750 characters (approx 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

Schemes for demonstration of the heat engine based on semiconductor quantum dots and diluted magnetic semiconductors will both be developed throughout the course of the proposed research program. The crucial advances made by our research group in recent years in the areas of quantum control in quantum dots and diluted magnetic semiconductors (described below) will lay the groundwork for development of heat engine concepts using these systems.

(1) Demonstration of Parallel Single Qubit Gates on Distant Solid State Qubits
We have recently demonstrated simultaneous control of the quantum states of exciton qubits in two different semiconductor quantum dots. This was achieved using the unique capabilities of our quantum control apparatus that allowed the phase of the broad bandwidth control pulse to be engineered in the frequency domain by iteratively adjusting the control Hamiltonian to achieve a target final quantum state of the two qubit system. This work is poised to have profound impact in the field of quantum control as it represents: (i) the first application of pulse shaping to optimize a quantum gate in any solid state system of qubits; and (ii) the first demonstration of parallel control of qubits in distant quantum dots. This demonstration lays the foundation for developing a small quantum simulator using complex instruction set quantum computing, and represents a crucial step forward on the path to developing scalable solid state quantum hardware. This work was recently published in A. Gamouras et al., Nano Lett. 13, 4666 (2013) and has been featured in invited talks at Photonics North 2013, and the Canadian Semiconductor Science and Technology Conference 2013.

(2) Development of Infrastructure for High-Fidelity Quantum Gates in Quantum Dots

Our group has established theoretical and experimental infrastructure for low-temperature microscopy and coherent control experiments targeted to the pursuit of subpicosecond quantum gates in semiconductor quantum dots with transition wavelengths in the range 1.1-1.6 m. The new capabilities provided by this infrastructure are unique in the world due to the combination of infrared all-optical excitation and detection on single quantum dots and the application of pulse shape control. Our numerical modeling capabilities for exciton dynamics in quantum dots were applied first to the C-ROT gate in R. Mathew, et al., Phys. Rev. B 84, 205322 (2011). The pulse shaping protocols developed using our new theoretical infrastructure were implemented experimentally using the new quantum control apparatus described above (A. Gamouras et al., J. Appl. Phys. 112, 014313 (2012)), demonstrating such a capability for the first time in the infrared spectral region. This work was featured in an invited talk at the 2012 Ultrafast Pulse Shaping Workshop.

(3) First measurement of Four-wave mixing response of a III-V Diluted Magnetic Semiconductor The utility of nonlinear spectroscopy for studying the electronic structure of GaMnAs was demonstrated in M. Yildirim et al., Phys. Rev. B 84, 121202(R) (2011)), in which we reported the first application of four-wave mixing spectroscopy to a III-Mn-V DMS. We showed that the enhanced sensitivity of nonlinear spectroscopy to fine features in the optical joint density of states provided the first clear signature of the effects of (s,p)-d hybridization on the valence states, and performed the first measurement of the Mn-hole spin-flip scattering time in GaMnAs (M. Yildirim et al., Appl. Phys. Lett. 101, 062403 (2012)). This work has been featured in invited talks at SPIE Optics and Photonics 2013, West Virginia University (2012), the CAP Congress 2011 and Magnetic North II 2011.

PART G - Personnel (Prof Stephen Barnett)

G1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Professor

Family Name

Barnett

First Name

Stephen

Second Name

Mark

Person identifier

53089547

Role

Partner Investigator

G2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

School of Physics and Astronomy

Postal Address Line 2

University of Glasgow

Locality

Glasgow

Postcode

G12 8QQ

Country

United Kingdom

G3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to ARC College or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

G4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 July 2014.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

G5. Are you an Indigenous Participant?

Indigenous Participant

No

G6. PhD Qualification

Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

01/10/1985

G7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	1985	Physics	Imperial College London

	Country
1	United Kingdom

G8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Professor of Quantum Optics	University of Glasgow, UK	Physics and Astronomy	2013

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes

G9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 July 2014 and beyond; for PIs it will generally be their main employer as at 1 July 2014).)

Organisation Name

University of Glasgow, UK

Type of Affiliation

Employee

G10. Time commitment (%FTE) to this Project

10

G11. Research Opportunity and Performance Evidence (ROPE)

G11.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i) 27 years since PhD

(ii) - (iii) I am a full-time physics professor. This entails the usual mix of research, teaching and admin duties. I am also carry out work for the Royal Society, the Royal Society of Edinburgh and the Institute of Physics. I am an editorial board member for Physical Review Letters, European Physical Journal D and Journal of Modern Optics.

It would be difficult to determine, accurately, the amount of time spent on each of these roles.

(iv) No career interruptions.

(v) I run a research group (all externally funded) which currently comprises three postdocs and four PhD students.

(vi) None come to mind.

G11.2. Recent significant publications and ARC grants (since 2003)

(Please attach a PDF with a list of your recent significant publications and ARC grants most relevant to this Proposal (10 Pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Prof Stephen M Barnett

Part 1 Publications since 2003

Scholarly Books

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

2. **S.M. Barnett**, "Quantum Information" (Oxford University Press, Oxford, 2009) ISBN 9780198527626.

Refereed journal articles

* 3. **S.M. Barnett** and J.A. Vaccaro, "Beyond Landauer erasure", Entropy, (accepted 31 October, 2013).
Eprint http://arxiv.org/abs/1310.7821

4. **S.M. Barnett**, "Comment on Trouble with the Lorentz Law of Force : Incompatibility with Special Relativity and Momentum Conservation", *Phys. Rev. Lett.* **110**, 089402 (2013).

5. X. M. Xi, T. Weiss, G. K. L. Wong, F. Biancalana, **S.M. Barnett**, M. J. Padgett and P. St. J. Russell, "Optical Activity in Twisted Solid-Core Photonic Crystal Fibers", *Phys. Rev. Lett.* **110**, 143903 (2013).

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

7. **S.M. Barnett**, K.T. McClusker, P.G. Kwiat and D.J. Gauthier, "Security of high-dimensional quantum key distribution protocols using Franson interferometers, Thomas Brougham", *J. Phys. B* **46**, 104010 (2013).

8. M.P.J. Lavery, F.C. Speirits, **S.M. Barnett** and M.J. Padgett, "Detection of a Spinning Object Using Lights Orbital Angular Momentum", *Science* **341**, 537 (2013).

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

10. F.C. Speirits and **S.M. Barnett**, "Do Waves Carrying Orbital Angular Momentum Possess Azimuthal Linear Momentum?", *Phys. Rev. Lett.* **111**, 103602 (2013).

11. **S.M. Barnett** and M.V. Berry, "Superweak momentum transfer near optical vortices", *Journal of Optics* **15**, 125701 (2013).

12. T. Weiss, G.K.L. Wong, F. Biancalana, **S.M. Barnett**, X.M. Xi and P.St.J. Russell, "Topological Zeeman effect and circular birefringence in twisted photonic crystal fibers", *J. Opt. Soc. Am. B* **30**, 2921 (2013).

13. F.M. Miatto, H.Di Lorenzo Pires, **S.M. Barnett** and M.P. van Exter, "Spatial Schmidt modes generated in parametric down-conversion", *Eur. Phys. J. D* **66**, 263 (2012).

14. R.P. Cameron and **S.M. Barnett**, "Electric-magnetic symmetry and Noethers theorem", *New Journal of Physics* **14**, 123019 (2012).

15. A.J. T. Colin, **S.M. Barnett** and J. Jeffers, "Measurement-driven dynamics for a coherently-excited atom", *Journal of Modern Optics* **59**, 1803 (2012).

16. **S.M. Barnett** and R. Loudon, "Optical Thomas-Reiche-Kuhn Sum Rules", *Phys. Rev. Lett.,* **108**, 013601 (2012).

17. J. Leach, R.E. Warburton, D.G. Ireland, F.Izdebski, **S.M. Barnett**, A.M. Yao, G.S. Buller and M.J. Padgett, "Quantum correlations in position, momentum, and intermediate bases for a full optical field of view", *Phys. Rev. A* **85**, 013827 (2012).

18. T. Brougham and **S.M. Barnett**, "Information communicated by entangled photon pairs", *Phys. Rev. A* **85**, 032322 (2012).

19. R.P. Cameron, **S.M. Barnett** and A.M. Yao, "Optical helicity, optical spin and related quantities in electromagnetic theory", *New Journal of Physics* **14**, 053050 (2012).

20. J. Romero, D. Giovannini, S. Franke-Arnold, S. M. Barnett and M. J. Padgett, "Increasing the dimension in high-dimensional two-photon orbital angular momentum entanglement", *Phys. Rev. A* **86**, 012334 (2012).

21. D. Giovannini, F. M. Miatto, J. Romero, **S.M. Barnett**, J. P. Woerdman and M. J. Padgett, "Determining the dimensionality of bipartite orbital-angular-momentum entanglement using multi-sector phase masks", *New Journal of Physics* **14**, 073046 (2012).

22. **S.M. Barnett**, R.P. Cameron and A.M. Yao, "Duplex symmetry and its relation to the conservation of optical helicity", *Phys. Rev. A* **86**, 013845 (2012).

23. F. M. Miatto, D. Giovannini, J. Romero, S. Franke-Arnold, **S.M. Barnett** and M. J. Padgett, "Bounds and optimisation of orbital angular momentum bandwidths within parametric down-conversion", *Eur. Phys. J. D* **66**, 178 (2012).

24. **S.M. Barnett** and S.J.D. Phoenix, "Asynchronous quantum key distribution on a relay network", *J. Mod. Opt.* **59**, 1349 (2012).

25. D.J. Saunders, M.S. Palsson, G.J. Pryde, A.J. Scott, **S.M. Barnett** and H.M. Wiseman, "The simplest demonstrations of quantum nonlicality", *New Journal of Physics* **14**, 113020 (2012).

26. J. Leach, R.E. Warburton, D.G. Ireland, F. Izdebski, **S.M. Barnett**, A.M. Yao, G.S. Buller and M.J. Padgett, "Quantum correlations in position, momentum, and intermediate bases for a full optical field of view", *Phys. Rev. A* **85** 013827 (2012).

*27. J.A. Vaccaro and **S.M. Barnett**, "Information erasure without an energy cost", *Proc. R. Soc. A* **467**, 1770-1778 (2011).
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Eprint http://arxiv.org/abs/1004.5330

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29. A.J.T. Colin, **S.M. Barnett** and J. Jeffers, "Programmed discrimination of qbits with added classical information", *Eur. Phys. J. D* **63** 463-472 (2011).

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31. B. Jack, P. Aursand, S. Franke-Arnold, D.G. Ireland, J. Leach, **S.M. Barnett** and M.J. Padgett, "Demonstration of the angular uncertainty principle for single photons", *J. Opt.* **13** 064017 (2011).

32. M. Stefanak, **S.M. Barnett**, B. Kollar, T. Kiss and I. Jex, "Directional correlations in quantum walks with two particles", *New J. Phys.* **13** 033029 (2011).

33. F.M. Miatto, A.M. Yao and **S.M. Barnett**, "Full characterization of the quantum spiral bandwidth of entangled biphotons", *Phys. Rev. A* **83** 033816 (2011).

34. J. Romero, J. Leach, B. Jack, M.R. Dennis, S. Franke-Arnold, **S.M. Barnett** and M.J. Padgett, "Entangled Optical Vortex Links", *Phys. Rev. Lett.* **106** 100407 (2011).

35. C.S. Hamilton, A. Gabris, I. Jex and **S.M. Barnett**, "Quantum walk with a four-dimensional coin", *New J. Phys.* **13** 013015 (2011).

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50. J. Leach, B. Jack, J. Romero, M. Ritsch-Marte, R.W. Boyd, A.K. Jha, **S.M. Barnett**, S. Franke-Arnold and M.J. Padgett "Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces", *Optics Express* **17** 8287-8293 (2009)

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53. A.K. Jha, B. Jack, E. Yao, J. Leach, R.W. Boyd, G.S. Buller, **S.M. Barnett**, S. Franke-Arnold and M.J. Padgett, "Fourier relationship between the angle and angular momentum of entangled photons", *Phys. Rev. A* **78** 043810 (2008).

54. J. Leach, A.J. Wright, J.B. Gotte, J.M. Girkin, L. Allen, S. Franke-Arnold, **S.M. Barnett** and M.J. Padgett, "'Aether drag' and moving images", *Phys. Rev. Lett.* **100** 153902 (2008).

55. P.W. Milonni, R. Loudon, P.R. Berman and **S.M. Barnett**, "Linear polarizabilities of two- and three-level atoms", Phys. Rev. **A77** 043835 (2008).

56. Sarah Croke, **S.M. Barnett** and Stig Stenholm, "Linear transformations of quantum states", *Ann. Phys.* **323** 893-906 (2008).

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58. S. Croke, E. Andersson and **S.M. Barnett**, "No-signaling bound on quantum state discrimination", *Phys. Rev. A* **77** 012113 (2008).

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61. R. Zambrini and **S.M. Barnett**, "Angular momentum of multimode and polarization patterns", *Optics Express* **15** 15214-15227 (2007)

62. D.R. Murray, **S.M. Barnett**, P. Öhberg and D. Gomila, "Elementary excitations of a Bose-Einstein condensate in an effective magnetic field", *Phys. Rev. A* **76** 053626 (2007)

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82. **S. M. Barnett**, J. Jeffers and J.D. Cresser, "From measurements to quantum friction", *J. Phys.: Cond. Matter* **18**, S401 (2006).

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118. M. Padgett, J. Leach, S. Franke-Arnold *et* al., "The lateral displacement of a moving image on transmission through a stationary glass window" in *Conference on Nature of Light - What are Photons* edited by C. Roychoudhuri, A.F. Kracklauer, K. Creath, Proceedings of SPIE **6664** 66640D (2007).

119. J.B. Goette, S. Franke-Arnold, R.Zambrini, *et* al., "Quantum formulation of fractional orbital angular momentum", J. Mod. Optics **54** 1723-1738 (2007).

Part 2 Details of ARC grants in the last 10 years

Not applicable.

G11.3. Ten career-best publications

(Please attach a PDF with a list of your ten career-best publications (4 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

Prof Stephen M Barnett

10 Best Publications

Citations from ISI Web of Science Cited Reference Search

1. D.T. Pegg and **S.M. Barnett**, "Phase Properties of the Quantized Single-Mode Electromagnetic-Field", Phys. Rev. **A39** 1665-1675 (1989).
   [citations: 660]
   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.

2. D.T. Pegg and **S.M. Barnett**, "Unitary Phase Operator in Quantum-Mechanics", Europhys. Lett. **6** 483-487 (1988)
   [citations: 494]
   Defined an operator that represents the phase of an optical field mode which, unlike previous attempts, attributed uniform random phase uncertainty to the vacuum.

3. **S.M. Barnett** and D.T. Pegg, "On the Hermitian Optical-Phase Operator", J. Mod. Opt. **36** 7-19 (1989)
   [citations: 405]
   Introduced the operator that has become widely accepted as the phase observable of a single mode optical field.

4. G. Gibson, J. Courtial, M.J. Padgett, M. Vasnetsov, V. Pasko, **S.M. Barnett** and S. Franke-Arnold, "Free-space information transfer using light beams carrying orbital angular momentum", Opt. Exp. **12** 5448-5456 (2004).
   [citations: 377]
   Shows that information encoded in orbital angular momentum states of a light is resistant to eavesdropping in the periphery of the beam.

5. J. Leach, M. J. Padgett, **S.M. Barnett**, S. Franke-Arnold, and J. Courtial, "Measuring the orbital angular momentum of a single photon", Phys. Rev. Lett. **88** 257901 (2002)
   [citations: 303]
   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.

6. B. Huttner and **S.M. Barnett**, "Quantization of the Electromagnetic-Field in Dielectrics", Phys. Rev. **A46** 4306-4322 (1992).
   [citations: 265]
   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. K. Wodkiewicz, P. L. Knight, S. J. Buckle and **S.M. Barnett**, "Squeezing and Superposition States", Phys. Rev. A **35** 2567-2577 (1987)
   [citations: 234]
   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.

8. **S.M. Barnett** and P. L. Knight, "Dissipation in a Fundamental Model of Quantum Optical Resonance", Phys. Rev. **A33** 2444-2448 (1986)
[citations: 223]

   Demonstrates the fragility of quantum effects by showing that the revivals in the Jaynes-Cummings model are strongly affected by dissipation even when the damping hardly affects the underlying oscillations.

9. R. Matloob, R. Loudon, **S.M. Barnett** and J. Jeffers, "Electromagnetic-Field Quantization in Absorbing Dielectrics" Phys. Rev. **A52** 4823-4838 (1995).
[citations: 169]

   Quantizes the electromagnetic field in dielectric media with both loss and dispersion and of various geometries: the infinite homogeneous dielectric, the semi-infinite dielectric, and the dielectric slab.

10. **S.M. Barnett**, P.L. Knight, "Thermofield Analysis of Squeezing and Statistical Mixtures in Quantum Optics", J. Opt. Soc. Am. B **2** 467-479 (1985).
[citations: 149]

    Introduced the thermofield representation, where mixed states are represented as pure states in an expanded-state space, to quantum optics. Now widely used to simplify the analysis of mixed fields.

G11.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

I have published 111 research articles in refereed journals since the beginning of 2003. This includes 16 in Physical Review Letters and 1 in Science. I have also published the postgraduate text book "Quantum Information" (Oxford University Press, 2009).

Research prizes and awards:

1994: Maxwell Medal and Prize for Theoretical Physics by the Institute of Physics, UK.

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 RSE

2007: Royal Society Wolfson Merit Award

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

2013: Dirac Medal of the Institute of Physics, UK

I am also a Fellow of the Instute of Physics and a Fellow of the Optical Society of America.

Citation Statistics:
H-index: 51
Total number of citations: 9836

G11.5. A statement on your most significant contributions to this research field of this Proposal

(Write a maximum of 3750 characters (approx 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

My most famous contribution was the discovery, with David Pegg, of the quantum phase operator for which I was awarded the Maxwell Medal.

The citation accompanying my election to the Royal Society highlighted my contributions to the study of quantum measurements and communications. This, also, was the topic of my prize lecture to the Royal Society of Edinburgh.

PART H - Research Support (LP140100797)

H1. Research support for all participants

(For each participant on this Proposal, provide details of research funding (ARC and other agencies in Australia and overseas) for the years 2013 to 2017 inclusive. That is, list all projects/proposals/fellowships awarded or requests submitted involving that participant for funding. Please refer to the Instructions to Applicants for submission requirements.)

Part G - Research Support

Description (all named investigators on any proposal or grant/project/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** (If applicable)	**2013** $'000	**2014** $'000	**2015** $'000	**2016** $'000	**2017** $'000
J. Vaccaro, L. Uribarri, K. Hall, S. Barnett, *Lightweight battery with more yield than a tonne of coal*, ARC, Linkage 2014	Yes	R	LP140100797		207	197	200	
D. Kielpinski, L. Uribarri, D. Hicks, *Bright x-ray beams from laser-driven microplasmas*, ARC, Linkage, 2014	No	R	LP140100813		171	150		
J. Vaccaro, *Information Erasure and Coherence in Quantum Dots*, Lockheed Martin Corporation	Yes	C		172				
K. Hall, *Ultrafast Optical Studies of Semiconductor Materials for Spintronics and Quantum Computing*, NSERC Canada, Discovery Grant	No	C		39	39	39	10	
K. Hall, *Canada Research Chair in Ultrafast Science*, NSERC Canada, Canada Research Chair	No	C		100	100	100	25	
S. Barnett, M. Padgett, *Challenges in Orbital Angular Momentum*, EPSRC UK	No	C		843	843			
K. Hall, *Solid State Quantum Coherence Storage*, Lockheed Martin Corporation	No	C		100				

PART I - Statements on progress of ARC-funded Projects (LP140100797)

I1. For each participant on this Proposal, please attach a statement detailing progress for each Project/Award/Fellowship involving that participant who has been awarded funding for 2012 under the ARC Discovery Projects, Discovery Indigenous Researchers Development, Discovery Indigenous, Discovery Early Career Researcher Award, Linkage Project or any ARC Fellowship scheme.

	Project ID	First named investigator	Scheme	Statement
1				
2				
3				

PART J - Additional Details (LP140100797)

J1. Other agencies

Have you submitted or do you intend to submit a similar Proposal to any other agency?

Other Agency Submission

No

If Yes, please select one of the following:

Other Agency Name

Not applicable for this candidate

If Other is selected above, please enter the full name of the agency:

Not applicable for this candidate