Institution: Imperial College London		
Unit of Assessment: 9 – Physics		
Title of case study: B9-6 Quantum optics research influencing Government policy and investment in Quantum Technologies		
Period when the underpinning research was undertaken: 2000-2016		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Prof Sir Peter Knight FRS	**Role(s) (e.g. job title):** Emeritus Prof and Senior Research Investigator	**Period(s) employed by submitting HEI:** 1979-present
Period when the claimed impact occurred: 1 August 2013 - 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The fundamental quantum optics research, including quantum computation and fast quantum gates, led by Knight at Imperial from 2000 resulted in Knight advising Government on quantum technologies from his appointments at NPL, the MoD and Imperial. He was pivotal in establishing the UK's 10-year £1Bn National Quantum Technologies Programme, of which the first phase (2014-2019) established four Quantum Technology Hubs, involving more than 20 universities and to date approximately 100 companies, with a Government investment of £380M. Following the publication of the Blackett Review "The Quantum Age" led by Knight in 2016, and the success of phase 1, a second phase commenced in 2019, extending the total Quantum Technologies funding beyond £1Bn.

2. Underpinning research (indicative maximum 500 words)

Knight's research group has been at the forefront of fundamental quantum optics for over forty years. From 2000 onwards, he developed significant programmes addressing quantum information technologies including experimental realisations of quantum information processing. Knight's research group highlighted and led the modelling of various mechanisms to realise quantum logic gates, initially investigating cold ions and atoms as a promising route **[1]**. He showed that quantum gates using a light-shifted, ac Stark effect could operate an order of magnitude faster than the more established experimental approach utilizing travelling wave schemes **[1]**.

His research group particularly focussed on generating and manipulating coherence and entanglement within dissipative environments and introduced methods and approaches widely adopted throughout the world. His highly cited papers in this period on optical entanglement, quantum walks to realise quantum algorithms, fast quantum gates, cold atom chips (particularly linked to experiments at Imperial) and trapped atoms in optical lattices **[2-6]** pioneered new directions that underpin the current priorities of the UK National Quantum Technologies Programme (NQTP). Knight and colleagues demonstrated that arrays of qubits in optical lattices had great potential for the realization of an atom register, modelling quantum computation based on an optical lattice with one atom per lattice and coherent manipulation between two different atomic ground states. Knight showed it was possible to perform one-qubit gates and two-qubit gates by Raman and tunnelling transitions respectively **[2]**. Knight also investigated the limitations of atom traps - microstructured surfaces which can be tailored to provide trapping geometries for the manipulation of the quantum state of cold atoms **[3]**. To minimize geometrical effects leading to system noise that can flip the atomic spin, Knight and colleagues demonstrated that the skin depth of the atom trap material used should be significantly different from the atom to surface distance **[3]**.

Extending his basic research on photonic quantum gates, Knight's quantum theory team collaborated with experimentalist J.L. O'Brien at Bristol University **[5]** and their work on fusion gates ultimately led to one of the most practical quantum computing platforms currently being developed in the USA by PsiQuantum (see case study B9-1). O'Brien is currently the CEO of PsiQuantum who are using a photonic approach to manufacture a universal quantum computer in a CMOS fab. The company employs several of Knight's former colleagues and collaborators.

Knight's theoretical research on quantum gate architectures and platforms, which were closely linked to collaborative experimental work at Imperial and elsewhere in the UK **[3, 5]**, had substantial national and international academic impact. This led to Knight working with the Research Councils, NPL, the MoD and other stakeholders to accelerate the UK development of quantum technologies. He was instrumental in creating the Interdisciplinary Research Centre (IRC) in Quantum Information Processing at Imperial College in 2004 and built on this to research new capabilities for quantum technologies and especially quantum computers.

Over the assessment period, Knight's excellence in research was recognised internationally through numerous prestigious awards and prizes. He is an ISI "Highly Cited Author", and his research monograph "Introductory Quantum Optics" (published 2004) has been cited over 2180 times (Google scholar) and is acknowledged as a major resource on non-classicality and its role in quantum photonics. As a result of this formative research, Knight was the obvious choice to advise the MoD and Government on quantum technologies. His influential research and advocacy led to the creation of the National Quantum Technology Programme which has invested in areas derived from Knight's quantum optics and quantum computation research.

3. References to the research (indicative maximum of six references)

[1] Fast quantum gates for cold trapped ions
D. Jonathan, M. B. Plenio, and P. L. Knight
Phys. Rev. A 62, 042307 https://doi.org/10.1103/PhysRevA.62.042307 – Published 13 September 2000

[2] Quantum Computation with a One-Dimensional Optical Lattice
Jiannis K. Pachos and Peter L. Knight
Phys. Rev. Lett. 91, 107902 https://doi.org/10.1103/PhysRevLett.91.107902 – Published 3 September 2003

[3] Thermal spin flips in atom chips
P. K. Rekdal, S. Scheel, P. L. Knight, and E. A. Hinds
Phys. Rev. A 70, 013811 https://doi.org/10.1103/PhysRevA.70.013811 – Published 28 July 2004

[4] Vibrational coherent quantum computation
M. Paternostro, M. S. Kim, and P. L. Knight
Phys. Rev. A 71, 022311 https://doi.org/10.1103/PhysRevA.71.022311 – Published 17 February 2005

[5] One-way quantum computation with four-dimensional photonic qudits
Jaewoo Joo, Peter L. Knight, Jeremy L. O'Brien, and Terry Rudolph
Phys. Rev. A 76, 052326 https://doi.org/10.1103/PhysRevA.76.052326 – Published 29 November 2007

[6] Cavity-Free Scheme for Nondestructive Detection of a Single Optical Photon
Keyu Xia (夏可宇), Mattias Johnsson, Peter L. Knight, and Jason Twamley
Phys. Rev. Lett. 116, 023601 https://doi.org/10.1103/PhysRevLett.116.023601 – Published 13 January 2016

4. Details of the impact (indicative maximum 750 words)

Research informing Government

Knight's influential research and international status in quantum optics, in particular his advances in, and advocacy of, quantum technology, resulted in his extensive participation in numerous UK panels and committees. The Chief Scientific Adviser to the MoD has worked closely with Knight. They write "*As a result of his international standing and underpinning research, Professor Knight has acted widely as an adviser to government, in diverse roles, serving on and chairing numerous committees, such as the Defence Scientific Advisory Committee and the MOD's Research and Development Board*" **[A].** His research has informed the direction of policy; "*Since 2000, Professor Knight's research outputs have had a particular focus on quantum information theory and his fundamental studies of photonic gates has underpinned research on practical realisations of quantum computers, which is a key aspect of the UK National Quantum Technologies Programme"* **[A]**. Using these positions Knight's campaigning has led to the UK Government's adoption of Quantum Technologies for potentially extensive commercial exploitation.

As a precursor of the National Programme, Knight (as a member of MoD's ISTA Register and MoD DSAC Chair) was instrumental in persuading the MoD to invest in a pilot programme, run through the Centre for Defence Enterprise (CDE, now DASA) on Atomic Clocks and Sensors with a call to pull together academia and industry on proof of concept technologies. This was widely regarded in government as the "toe in the water" test of appetite to deliver novel engineering capabilities based on quantum technologies. The Chief Scientific Adviser recalls that "*Professor Knight had also originally persuaded the MOD to invest in a pilot programme"* **[A]**. This is also confirmed by Dstl, who states that Knight's work and advice on Quantum Technologies to the MoD and other government departments has *"given the UK a world leading position in the global quantum technology race, ensured the MoD recognised the game changing opportunities of the new technologies and began investing in R&D in 2013 to develop quantum clocks and other quantum sensors for early adopter advantage"*. In addition stating of Knight's work, "*influencing UK Government policy, resulting in a focus on quantum technologies, has had a transformative impact on quantum technology R&D in the UK."* **[B].**

Influencing UK Government policy and the National Quantum Technology Programme

Following the CDE call, Knight, briefed David Willetts, the then Science Minister (who was developing the concept of the 8 Great Technologies) on quantum technologies and helped his Private Office to arrange ministerial briefings from the community which shaped the Phase 1 NQTP announcement of the initial £270M investment in the 2013 Autumn statement **[A].** "*Through his* [Knight's] *direct lobbying at Cabinet level, he convinced the UK government of the importance of his research and to recognise the enormous potential of quantum technologies*" **[A].**

Creation of the National Programme

The creation of NQTP Phase 1 from 2014-2019 led to the establishment of an RCUK/BIS (as it was then) Strategic Advisory Board, with Knight as the leading scientific expert as a member. Knight was the lead author of the UK Government Office of Science, Blackett Review "The Quantum Age" in November 2016, acknowledged as the main driver that led to the second 5-year tranche of funding for the programme **[C].** Sir Mark Walport, the Government Chief Scientific Adviser at the time, highlighted Knight's role stating "*I would like to thank the many contributors for the support they have provided to this review, and especially Professor Sir Peter Knight for his leadership on this project*." As a result of the success of the Report, Mark Walport, UKRI CEO asked Knight to write the "Vision Piece" for UKRI for Phase 2 of the NQTP which resulted in HMT funding of a second 5 years support for the Programme **[D]**. Also, in June 2018, Knight gave oral evidence to the Science and Technology Committee **[E]**. The Government's response to this committee's report and the 2016 Blackett report on Quantum Technologies was to fund phase 2 of the NQTP taking the level of investment in the programme over £800M and to create an Executive Board to oversee the second phase. This board was a recommendation from the 2016 Blackett report **[F]**.

Knight also put together industrially led consortia to deliver prototype demonstrators of commercial relevance in quantum sensing, communication and imaging. Following this success, Knight was invited to be the lead technical author of the ISCF Quantum Challenge "Wave 2" which secured £153M of support from BEIS and £205M matching commitment from industry to accelerate industry led implementation projects. Announced in June 2019, it is an important element of the national programme strategy to engage with industry and support the commercialising of quantum technologies **[G]**. In addition, Knight worked with UKRI to refresh the QT Research Hubs for Phase 2, helping to lead community workshops on new opportunities and to identify and bring on board new members to the Hub teams. To date, government funding for Quantum Technologies has exceeded £1 billion **[A]**.

On the award of the Faraday Medal of the Institute of Engineering and Technology to Knight for his formative work on engineering aspects of quantum technology, the citation included *"…. for his outstanding contribution in the field of quantum engineering. His pivotal role in conceiving, designing and delivering the National Quantum Technologies Programme has put the UK quantum science and engineering at the front of the global race to establish the second information revolution"* **[H].**

Knight was lead technical author of the Business Case for BEIS for the National Quantum Computing Centre at Harwell, announced in the 2018 Budget with a purse of nearly £100M over 5 years included in the additional £235m for the NQTP **[A].** He is now a member of the Project Board for UKRI to build the new Centre. He has also chaired in 2019-2020 the Quantum Expert Group Technical Road mapping for BEIS on future opportunities in Quantum Computing as part of the work for the Comprehensive Spending Review **[I]**. Knight is now Chair of the NQTP Phase 2 SAB and is Technical Advisor to Innovate UK on Quantum Technology and the accelerating industrial exploitation of the area.

Impact of the National Quantum Technologies Programme

The NQTP has generated substantial industrial commitment, with approximately 100 companies involved in associated industry-led Industrial Strategy Challenge Fund activities. The ISCF Challenge Director, states that "*The creation of the Quantum Hubs enabled some 100 companies to become involved with the Programme. The ISCF programmes now have secured over £170M of public funding which is expected to attract over £200M of industrial funding. 177 businesses and 44 research organisations have applied for funding to date and - in round figures - 40 projects (involving 90 companies and 30 research organisations) have been launched."* He goes on to say, "*The high levels of industry engagement and commitment to date indicate that your* [Peter Knight's] *research and personal contribution have taken us well down this road and have laid the foundations for an ambitious large scale world leading public and privately funded programme."* **[J]**

Quantum technology related start-ups in the UK now exceed 32, with over 170 new employees and private investment of over £70M; current estimates by BEIS show this is growing rapidly. For example, the Networked Quantum Information Technologies hub, one of four in the NQTP, collaborated and partnered with over 140 companies, 34 industry-partnered projects, and at least 5 spinouts.

One such example is, Teledyne e2v, a world leader in the design and manufacture of specialist electronic components and subsystems. The CTO & Head of Quantum Technologies, Space & Quantum at Teledyne e2v writes "*Over the last 6 years they have invested over £10M of company funds in developing a new technology platform and businesses in Quantum Technologies.*[…] *the Teledyne e2v activity has grown to over 40 people and is close to launching its first products. Our investment has without doubt been accelerated by the innovative National Quantum Technology Programme where during Phase 1 Teledyne e2v was the largest industrial investor and CR&D partner in the whole programme leading supply chain developments in multiple projects, of total value >£25M across c. 30 partners.*" **[K].** Knight's fundamental research and leadership in Quantum Technologies has been foundational to this national success - "[…] *without Knight I very* *much doubt that we would have a joined up National QT Programme in the UK at all, and certainly not a £1Bn scale one."* **[K].**

The UK had an early lead in QT but other countries since have proposed similar programmes, including the USA's major National Quantum Initiative launched in 2018 by the White House (Knight was one of only 3 non-Americans present at the White House launch; the European Union Quantum Flagship is of similar size and both follow exactly the focus identified by Knight for the UK programme: Imaging, Sensors and Timing, Communication and Quantum information Processing. "*The reach and significance of his fundamental studies has resulted in major programmes in quantum technology being instigated in Germany and the United States of America, while the European Union Quantum Flagship has closely followed the UK's model both in content and funding levels."* **[A].**

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter from MoD Chief Scientific Advisor
[B] Letter from DSTL Senior Fellow in Quantum Technologies
[C] UK government review of Quantum Technologies: https://www.gov.uk/government/publications/quantum-technologies-blackett-review (Archived here)
[D] Summary note of the UK National Quantum Technologies Programme Strategic Advisory Board Meeting http://uknqt.epsrc.ac.uk/files/sab-notes-october-2017/ (Archived here)
[E] Science and Technology Committee Oral evidence: Quantum technologies, Tuesday 5 June 2018 http://data.parliament.uk/WrittenEvidence/CommitteeEvidence.svc/EvidenceDocument/Science%20and%20Technology/Quantum%20technologies/Oral/84595.html (Archived here)
[F] Quantum technologies: Government Response to the Committee's Twelfth Report https://publications.parliament.uk/pa/cm201719/cmselect/cmsctech/2030/203002.htm#footnote-002 (Archived here)
[G] New £153 million programme to commercialise UK's quantum tech: https://www.gov.uk/government/news/new-153-million-programme-to-commercialise-uks-quantum-tech (Archived here)
[H] Press release relating to IET Achievement Awards: https://www.theiet.org/media/press-releases/press-releases-2019/25-october-2019-world-leading-engineers-win-at-iet-achievement-awards/ (Archived here)
[I] Letter from Strategic Policy and Quantum Technologies Lead, GCHQ
[J] Letter ISCF Challenge Director at Innovate UK, UKRI
[K] Letter from CTO & Head of Quantum Technologies, Space & Quantum at Teledyne e2v