Institution: University of Bristol

Unit of Assessment: 9 - PHYSICS

a. Overview

The School is recognised internationally for the quality of its research and since RAE2008, the School has seen substantial growth, both in its income and infrastructure. Of the 48 Category A staff entered in REF2014, 11 are new appointees, including 3 in a new grouping, the Centre for Quantum Photonics (CQP), which is carrying out pioneering research at the interface between Physics and Electrical Engineering (EE).

Staff were recipients of a number of awards during the REF period, including Fellowship of the Royal Society (Miles), the John Stewart Bell prize for quantum mechanics (Popescu), 5 ERC awards (Popescu, O'Brien, Rademacker, Royall, Thompson), 4 Wolfson Royal Society Research Merit Awards (Miles, Popescu, O'Brien and Hussey) and an RAEng Chair (O'Brien). Research highlights during the REF period include:

- Bremer and colleagues discovering one of the most distant known galaxies (*Nature 2010*)
- the CQP demonstrating manipulation of multiphoton entanglement in waveguide quantum circuits *(Nature Photonics 2009),* quantum walks of correlated photons *(Science 2010)*, a quantum delayed-choice experiment *(Science 2012)*, and experimental realisation of Shor's quantum factoring algorithm using qubit recycling *(Nature Photonics 2012)*
- the Correlated Electron Systems (CES) group discovering 'extended' criticality (*Science 2009*), quantum criticality in pnictides (*Science 2012*), quantum oscillations in overdoped cuprates (*Nature 2008*) and charge order in underdoped cuprates (*Nature Physics 2012)*
- Antognozzi and Miles imaging ultra-delicate peptide nanostructures with their unique lateral molecular force microscope (*Science 2013*)
- Dennis and his team creating the first isolated knotted light vortices (*Nature Physics 2010*)

The £11M Nanoscience and Quantum Information (NSQI) building adjoining Physics opened in 2008. It houses a suite of laboratories whose noise levels are considered among the lowest in the world as well as the Bristol Centre for Functional Nanomaterials (BCFN), one of the EPSRC's flagship doctoral training centres that was recently renewed for a further five years of graduate entry. In 2011, the University initiated a further £4M investment in new infrastructure and facilities, including a clean room and material synthesis facility. This is in addition to the new £8M investment in BlueCrystal high-performance computers. In 2013, the Interface Analysis Centre (IAC), a successful industry-focussed materials research centre, was integrated into Physics to strengthen its ties with research groups within the School and to increase industrial contacts.

There are now seven research groups in Physics: **Astrophysics (Astro)**, **CES**, **CQP**, **Micro and Nanostructural Materials (MNM)**, **Nanophysics and Soft Matter (NSM), PP** and **Theoretical Physics (TP)**. Due to its highly interdisciplinary nature, the CQP submission is split between Physics and EE, in recognition of the relevance to both disciplines of their high-impact, high quality research. The IAC's research activities are also interdisciplinary, and while all IAC staff are now located within Physics and a number of their impact case studies, submitted to UoA9, contain strong physics content, their research outputs are being submitted for this REF exercise to other UoAs within the University.

b. Research strategy

The School's research activity spans a wide spectrum, from cosmology to nanoscience and from quantum matter to elementary particle physics. The strategic management of the School's research is organized through the Research Steering Committee (RSC), chaired by the Head of School (HoS) and attended by Heads of Group (HoGs) and the Directors of Research, External Affairs and the IAC. The School's fundamental philosophy is to provide the space and freedom for each Group to define its own research direction but also to encourage interactions, both between Groups and with other schools/faculties within the University. Input from junior staff is fed into the RSC via the Early Careers Forum; a sounding board for new research ideas and initiatives.

Overall, the School's research strategy has 4 key strands:

1. **Building on core research strengths**. With the establishment of seven research groups, appointments are sought to reinforce areas where the School clearly demonstrates research excellence, as illustrated with the recent appointments in CES (Friedemann and Bell) to broaden their materials and techniques base, in Theory (van Wezel and Short) to strengthen the Group's efforts in correlated electrons and quantum information, and the recent proleptic lectureship for a Leverhulme Fellow (Matthews) in the CQP.
2. **Building on University (UoB) investments.** The School continues to benefit from UoB investments in its research environment. Much of our experimental research is undertaken in the superb laboratories in the NSQI building next door, while our collaborative nano-research in the biomedical/bioscience areas will soon benefit from the £65M Life Sciences building due to open in 2014, also adjacent to Physics. CQP's vision of new quantum technologies for 'real world' applications has attracted significant (>£1M) UoB investment to facilitate their ambitious plans and enhance their research environment. The PP group benefitted from significant investment in the HPC.
3. **Building research links across the University**. Collaborative research links across the Faculties of Science and Engineering are core to the School's research strategy, with joint appointments between Chemistry and the MNM and NSM groups in addition to those in the CQP. Future joint appointments building on links with EE in power electronics and with Earth Sciences in the area of exoplanets are also planned. The School is also building links with the UoB's flagship multidisciplinary research centres: the Elizabeth Blackwell Institute for Health Research and the Cabot Institute for environmental change, while Scott (IAC) is the Bristol director of the Bristol-Oxford Nuclear Research Centre.
4. **Building industrial links.** The School plans to grow and further embed the research that is industrially focussed in the IAC, the CQP and in the MNM group. The School has recently set up an Industrial Advisory Board to explore and exploit more fully the industrial relevance of its research and to tap new sources of funding. The Board is chaired by Prof. P. Dobson, Chief Executive of Begbroke Science Park and strategic advisor to RCUK, and its membership includes leading UK industrialists.

Below, we highlight the achievements and future strategies of the 7 research groups (members in square brackets, *Group Heads in italics*, UoA panel in curved brackets - if not Physics).

Astrophysics [*Birkinshaw*, Bremer, Leinhardt, Maughan, Phillipps, Worrall, Young]

Achievements Significant results from the Group on the structure and energetics of radio lobes from active galaxies have validated assumptions about the "equipartition" of the radio-emitting plasma, thus putting physical interpretation of radio outflows on a more solid footing. Deep near-IR and optical observations by the Group have found some of the highest-redshift galaxies currently known, and molecular line observations have found evidence for gas in optically-undetected galaxies in young clusters. The Group's work on the gas and galaxy populations in clusters at moderate and high redshift has led to more precise methods of measuring the masses of clusters, helping to define the manner in which structure forms in the Universe. Following on from Bristol's earlier discovery of ultra-compact dwarfs, the Group has further studied the galaxy populations in nearby clusters and how galaxies evolve. TOPCAT, the Group's catalogue-handling software, is extensively used by the worldwide astrophysics community and is being adapted for new European Space Agency (ESA) missions.

Strategy / Objectives The Group's future activities will focus on the formation and evolution of galaxies and clusters of galaxies and on the physics of active galaxies and black hole systems. Growth within the field of planetary formation is also planned. The research will be based on the observational opportunities offered by the largest ground-based and satellite observatories, with group members active in collaborations using many major observatories, and on the computational opportunities offered by University, national, and international supercomputers. The major Group objectives lie in addressing profound questions about the manner in which structure forms in the Universe, the feedback of energy and fields into that developing structure, the "dark" constituents of the Universe, the properties of black holes, and the variety of planetary systems. The Group will

focus more on the magnetic properties of the intergalactic medium and on molecular spectroscopy in the context of cosmology and planetary physics. The Group also expects to increase its major involvement in the XXL survey with the aim of extracting precise cosmological data. They will develop catalogue data exploration tools for the GAIA mission and will continue to investigate the early stages of galaxy formation using the VLT and eventually the E-ELT telescopes. The formation and evolution of exoplanetary systems will be explored in collaboration with Earth Sciences.

Centre for Quantum Photonics [Matthews, *O'Brien*, Oulton (UoA15), Peruzzo, Rarity (UoA15), Thompson (UoA15)]

Achievements The CQP has taken important steps towards producing quantum technologies, with many developments published in high impact journals (e.g, 5 in *Science*, 2 in *PNAS* and 7 in the *Nature* journals) during the REF period. In 2008, the Group launched the field of integrated quantum photonics, showing that photonic circuits can be implemented on-chip in waveguide architectures, work that has garnered numerous awards. This approach was used to realise a quantum walk of two correlated photons in a 21-waveguide array that was featured in the *Financial Times* in 2010. The Group has also implemented the first quantum algorithm on a chip, an important step-change in the field enabling all-optical computing to go from practically unfeasible to a leading approach to quantum computing. They also demonstrated quantum metrology on a chip and in collaboration with a physiologist, used it to measure the concentration of a blood protein.

Strategy / Objectives The Group's vision is to become the global centre for research, development and entrepreneurship in the new quantum technology revolution. It will continue to solve the difficult physics and engineering problems that will enable quantum technologies to become a reality. The three areas of particular interest for exploitation are quantum-enhanced sensors, secure communication systems and networks and quantum information processors. In the next 5 years, the Group will undertake theoretical and experimental research to deliver convincing prototype technology demonstrators in these application domains delivering ~30 physical qubits. Theoretical studies will focus on error models, fault tolerances, multiplexing and large scale architectures; experimental work on waveguide sources, integrated quantum circuits and single photon detectors. Collaborations with the Quantum Information grouping at Bristol, national and international partners as well as strong industrial engagement will be critical for the Group's success. The Group will also seek to extend its experimental facilities, e.g. through the new UoB clean room that it will use for chip preparation and fabrication.

Correlated Electron Systems [Alam, Bell, *Carrington*, Dugdale, Friedemann, Hayden, Hussey]

Achievements The iron-based superconductors, discovered in 2008, have been a major research activity of the Group since the last RAE. The Group's focus has been on the fundamental origin of superconductivity in these materials, through a combined study of Fermi surface topology, superconducting gap structure and magnetic excitations. The Group has also continued to be very active in the field of high-T_c cuprate superconductors with particular emphasis on elucidating the nature and origin of the Fermi surface and its reconstruction found in underdoped cuprates. A new avenue of study is quasi-one-dimensional $Li_{0.9}Mo_6O_{17}$ which is a candidate model material for the long sought-after Luttinger liquid metallic ground state. The Group's work has appeared regularly in high impact journals, with 7 articles in *Nature* / *Nature Physics* etc, 2 in *Science*, 2 in *PNAS* and 12 in *PRL* published during the REF period.

Strategy / Objectives The Group aims to maintain its leading position by performing high-impact experiments that directly address fundamental properties of strongly correlated electron behaviour. Two new areas of focus are correlated behaviour at surfaces and interfaces (e.g. superconductivity and topological insulators) and competing order (e.g. cuprates and heavy fermions). The Group's strategy is to have access to the best samples and use cutting-edge experimental probes. The two new academic appointments in CES reflect this strategy: Bell has expertise in oxide heterostructures while Friedemann has expertise in heavy fermions and high-pressure techniques. The School's new £0.5M sample synthesis facility has expanded the range and quality of materials which the Group can prepare in Bristol. The Group also aims to upgrade its two-dimensional positron ACAR apparatus and play a leading role in the new £5M inelastic X-ray scattering spectrometer (where Hayden is Chair of the User Group) and the ARPES (angle-resolved photoemission spectroscopy) beam line at Diamond.

Micro and Nanostructural Materials [Cherns, Fox (UoA8), *Kuball*, Sarua, Schwarzacher, Uren, Vasiljevic]

Achievements The Group is one of the leading European groups in Gallium Nitride (GaN) semiconductor electronics and its research is now on the threshold of commercialisation. The Group collaborates with key global industrial partners such as TriQuint, with whom they made the first high performance integrated GaN-diamond microwave power transistor, a project recognised as significant by the US Defense Advanced Projects agency. The Group has developed holographic and cathodeluminescence techniques to study GaN light emitting diodes and has identified new mechanisms for the generation and annihilation of dislocations in nanostructured and laterally overgrown films enabling low-cost solar cells. Group research into the interplay of uniaxial and cubic anisotropies in cobalt-doped nanoparticles, has enabled the fabrication of large (>300 μm) three-dimensional periodic arrays of magnetic nanoparticles, that show promise as magnonic metamaterials. The Group has also developed novel electro-deposited nanocatalysts for high efficiency, low cost fuel cells. Three Great Western Research Fellows (Fox, Sarua and Vasiljevic) became permanent group members during the REF period.

Strategy / Objectives The Group continues on its path to becoming world leading in semiconductor device reliability and to investigating technologically relevant physical phenomena that are critically dependent on micro- and nanostructure in semiconductor (wide band-gap) materials and devices, magnetic materials and metallic surfaces. The Group has been strengthened by the appointment of an Industrial Research Professor (Uren). The Group's Centre for Device Thermography recently formed the Bristol Power Electronics Innovation Centre with the Electrical Energy Management group in EE to develop novel power electronics and to contribute to setting the overall UK agenda in this strategic area. Future research in nanomagnetism will focus on magnetic nanoparticles as a probe of biomolecule dynamics, particularly at low temperatures, and on molecular spintronics. The Group also aims for further progress in the fuel and solar cell areas, benefitting from the purchase of a new scanning probe microscope which enables nm-resolution of surface electronic properties.

Nanophysics and Soft Matter [Antognozzi, Barnes, Gersen, Gimzewski, Hanna, Hoerber, McMaster, *Miles*, Richardson, Royall (UoA8), Seddon]

Achievements A particular strength of the Group is its development of scientifically-enabling, cutting-edge instrumentation in scanning probe microscopy, optics, X-ray and neutron scattering with all the associated research underpinned by computer simulations. The high-speed contact-mode atomic force microscope (AFM) maintained its position as the fastest in the world by an order of magnitude. High-speed oxidative writing and simultaneous imaging have been demonstrated on silicon. The lateral molecular force microscope has been developed for combined extreme force sensitivity and biomolecular force measurements, while time-resolved scanning near-field optical microscopy (SNOM) has enabled the full evolution of local EM fields to be studied on ultrafast timescales by single-point measurements. The Group has developed a unique capability for near-field imaging in the mid-IR with chemical specificity, while photonic force microscopy, invented by the Group, has been applied to a range of biomolecules. These techniques have had an influence in many diverse areas of research ranging from proteins and DNA to the study of minerals and photonic band gaps. The Group have also deepened our understanding of the structure of novel glasses and liquid crystals.

Strategy / Objectives Characterising and understanding nanoscale materials – their structure, properties and function - is a common goal of the Group, achieved using its suite of complementary techniques. This emphasis means the Group is strategically placed to engage in a wide range of interdisciplinary collaboration, from the biophysics of cells, membranes and molecules to structural studies of liquid crystals, surfaces and semiconducting glasses. The Group will continue to develop outstanding scanning probe capability, with some techniques being used in combination, e.g. holographic tweezers controlled AFM, photonic force microscopy, SNOM and levitation for container-less neutron and x-ray scattering. The future scientific focus of the Group will be the study of individual and coupled nanosystems with applications in advanced materials, photonics and medicine, e.g., single biomolecular recognition, mechanics and processes associated with signalling and energy transduction. The recent adjoint appointment of Prof. J. Gimzewski (UCLA) opens up new areas of application, particularly in biology, for the Group's diverse techniques.

Particle Physics [Brook, Flaecher, Goldstein, Heath, *Newbold*, Rademacker, Velthuis]

Achievements The experimental activities at DESY and SLAC, now concluded, allowed important insights into proton structure, hard and soft QCD, and CP-violation. The Group is now highly active within the CMS and LHCb collaborations in data analysis, detector development and operations, having played an important role in the design of both experiments, in particular the one with CMS, that enabled the discovery of the Higgs boson. Group members have held, and continue to hold, significant management roles within international collaborations, and have driven the physics programme in key areas. Their work at CMS encompasses the search for supersymmetry and exotic phenomena indicative of Grand Unified Theory-scale physics, as well as the precision measurement of top quark properties. In LHCb, the Group leads the measurement of the CP-violating phase γ, and of CP-violation in charm. During the REF period, detector development and instrumentation programmes have been re-invigorated by new facilities within the School, and applied to a number of diverse areas. Most recently, the Group has taken a leading role in the upgrade of the LHC detectors for the increase of collision energy in 2015, and has maintained a role in preparations for the International Linear Collider (ILC). Their growing presence in these areas has been recognised with substantially increased funding from both STFC and the EU. Finally, the Group has four projects partly or solely funded by industry.

Strategy / Objectives The Group will focus on what it considers are the most exciting scientific projects. Using the CMS detector, the Group will exploit the LHC's increased energy and luminosity to increase the reach of searches for direct dark matter production, and to examine with unprecedented precision the properties of the top quark. Within LHCb, the Group will use novel approaches to analyse multi-body decays of B mesons to measure accurately the CKM angle γ, and to look for direct evidence of new physics at high mass scales. This work will be complemented by a search for ultra-rare (beyond the Standard Model) decays of kaons at NA62. The Group will also build upon its expertise in data analysis, electronics and detector construction as it seeks to expand its size and capabilities and continue to play a leading role in the operation and upgrade of the LHCb and CMS detectors. It will also begin a new activity in the design and optimisation of a large detector for the ILC. Finally, the Group will continue its successful detector development programme, and seek new industrial and academic collaborations across a range of disciplines.

Theoretical Physics [Annett, Berry, Brunner, *Dennis*, Gradhand, Popescu, Short, van Wezel]

Achievements The Group has made major advances in our understanding of quantum non-locality and fundamental contributions to the foundations of thermodynamics and statistical physics. In particular, members of the Group proved directly from the basic equations of motion that almost any quantum system interacting with a larger environment will reach an equilibrium state, thus proving one of the basic postulates of statistical mechanics. The quantum delayed-choice experiment, published in *Science*, arose through a close collaboration between TP and the CQP. Group research on the theory of structured light has also made significant advances, including the design of super-resolving lenses and vortex beams in relativistic electron beams. Recently, abstract knot theory was applied to engineer knotted optical vortices into Gaussian laser beams, a result that was later confirmed experimentally. The Group has strong links with the CES and other experimental groups worldwide on materials with novel quantum ground states driven by strong electron correlation. The Group has developed a theory of intrinsic orbital magnetism and Kerr effect for multiband superconductors with time reversal symmetry breaking triplet pairing states, has proposed possible candidate materials for triplet pairing and has developed a complete theory of chiral charge density waves driven by orbital ordering.

Strategy / Objectives Common themes unite the Group's diverse and interdisciplinary research interests: fundamental quantum mechanics, collective and topological electronic properties of materials, and applications of geometry and topology to optics and wave mechanics. The recent appointments of Short and van Wezel will further enhance the Group's strong ties with experimental groups within Physics (particularly the CQP, CES and NSM groups) as well as more widely in the University, (e.g. Chemistry, Mathematics and Philosophy). Our future goals are to illuminate further the foundations of quantum mechanics, especially linking with fundamental thermodynamics; developing new optical imaging schemes inspired by techniques from quantum measurement and singular optics; and understanding novel phases of condensed matter with

chiral and topological order. The major upgrade to the BlueCrystal HPC facility is enhancing the Group's ability to carry out large-scale computation in condensed matter and topological physics, complementing its renowned theoretical and mathematical expertise. Stronger interaction with Mathematics and with other experimental groups in Physics, including Astro and PP, is also envisaged. Worldwide collaborations are supported by recent visiting professorships to H. Briegel (Innsbruck) and S. Whittington (Toronto).

c. People, including:

i. Staffing strategy and staff development

The School recognises that in order for its staff to deliver excellent, high-impact research, it must provide them with the time and space to focus on their research in a stimulating and supportive environment. The School is committed to help its academics reach their potential as research leaders and its staffing and development strategy reflects this:

1. **Making and supporting high calibre new appointments**. The School continually seeks to appoint high-calibre junior staff into academic positions, as evidenced with the recent appointments of Bell, Flaecher, Friedeman, Matthews, Short and van Wezel. All new appointees are given a reduced teaching load in the first two years and priority in the allocation of PhD students, experimentalists were given substantial (£30k) start-up funds, while van Wezel was given £5k to organize a series of workshops.
2. **Making joint appointments across Schools, Faculties, National Laboratories**. Joint appointments with other Schools/Faculties have helped stimulate interdisciplinary working within the School – all academics in the CQP group have joint appointments with EE while two other staff (Fox and Royall) have joint appointments with Chemistry. Discussions are ongoing with the Diamond Synchrotron at the RAL to establish new joint academic posts.
3. **Enabling research.** The School has introduced a number of schemes during the REF period to give staff more academic freedom to explore and focus on their research:
   a. **Sabbatical Scheme.** The School was the first in the Faculty of Science to introduce a formal mechanism for sabbaticals to enable staff to establish a new research direction, to complete a major research project, or to develop new grant opportunities. Goldstein (PP), for example, spent 7 months at CERN, raising both his productivity and his profile, while Sarua (MNM) wrote his first successful grant proposal.
   b. **Research Incentive Scheme.** This scheme, set up in the School of Physics in 2011, serves as a starting point for new research initiatives with the potential to pump-prime future grant applications. Intended primarily for ECRs, applications are reviewed annually by the RSC. One such award allowed Maughan (Astro) to become involved in the redesign of the Athena satellite into Athena+ and to be a significant contributor to a recent white paper which forms the basis of the mission proposal to the ESA.
   c. **Protected Research Time (PRT).** The School established this scheme in 2012 with the aim of ensuring that academics can optimize their research output by blocking out their time in a way that reflects their most efficient working patterns. Teaching and administration duties are assigned according to the individual academic's PRT preferences.
4. **Supporting Early Career Researchers.** The School has a well-established and active mentoring scheme in place. Through it, experienced colleagues provide guidance and advice to new appointees on research management, grant applications, PhD supervision and teaching matters. The development and integration of new staff is assisted by their association with a research group, thus promoting collaboration with established staff through shared facilities and frequently, joint grant applications. A teaching mentor serves as an important medium to ensure high quality teaching is delivered without loss of research productivity.
5. **Reviewing and managing performance.** The Staff Review and Development scheme provides a mechanism for identifying and removing barriers to better teaching and research, and for the identification of staff training needs. On-going monitoring, advice and support for academic staff is provided by the HoS and HoGs. Contract research staff are reviewed by their

supervisor or by the HoG. All individuals are encouraged to take advantage of appropriate University staff development opportunities. Lecturers are reviewed annually by their HoG (or deputy); more senior academic staff by the HoS.

6. **Addressing the gender balance.** Despite the recent appointments of 3 new female staff members (Leinhardt, Seddon, Vasiljevic), the male to female ratio among academic staff and students remains disproportionately high. The School is working actively to try and address this issue as part of the Institute of Physics (IoP) JUNO programme. In 2012, the School was awarded 'practitioner' status within the JUNO scheme.
7. **Research Concordat:** The University's Concordat ensures that research staff are supported and nurtured during their career development. It sets out the expectations and responsibilities of researchers, their managers, employers and funders in seven key areas. In recognition of the Concordat action plan, the UoB was awarded the HR Excellence in Research badge by the EU Commission in October 2010.

ii. Research students

The total number of home students undertaking a PhD rose from 59 in 2008/09 to 93 in 2012/13, and while overseas numbers remained steady over the first 4 years of the REF period, in the range 10-14, that number rose steeply to 20 in 2012/13. The majority of overseas students come from Thailand, China, South America and the Middle East. The UoB recently signed partnership agreements with the Universities of Kyoto and Uni-camp (Brazil) leading to opportunities for postgraduate student exchange. The School also has students funded directly from companies, such as AWE UK and TriQuint USA.

The BCFN is a flagship EPSRC centre for doctoral training that recently had its funding renewed. The BCFN offers a 1-year MSc in Nanoscience and Functional Nanomaterials as well as the 4-year PhD programme, with every PhD student having a supervisor from at least two different schools. In addition to the BCFN, the School has recently been instrumental in securing EPSRC funding for a new CDT in Quantum Engineering (shared between Physics, Mathematics and EE). The condensed matter community, meanwhile, have been served by the ONYX Graduate Training Alliance, a bottom-up venture between the universities of Bath, Bristol and Exeter offering graduate students in the -onics sector (electronics, photonics, plasmonics, etc.) access to the varied expertise available at all three institutes. The PP group runs a well-established graduate training programme together with the Midland Alliance through the Access Grid, while the Astro group has initiated a series of research days whereby students meet with their peers from Exeter and Cardiff to network and present their research.

The Physics Graduate School provides a focus for PhD students, developing research skills through a lecture/training programme, arranging social events and monitoring progress. It runs an annual conference at which all first year students present a poster and all second years give a talk. The Graduate School also ensures that all postgraduates are trained in transferable skills and can interact with peers from diverse research activities. Students also receive support to attend summer schools, conferences, workshops, and 'Group Away Days'.

Finally, the newly created Bristol Doctoral College will oversee development of doctoral education across the UoB, providing a clear and visible focus for its postgraduate research and training. Its primary aims are to support a high-quality student experience, to build on best practice within each School and to ensure better skills training across the University.

d. Income, infrastructure and facilities

Research Income

The School has been awarded over £38M in new grant funding over the full REF period since January 2008. Of the £28M tabled in REF4b/c (equivalent sum in RAE2008 was £17M), around 73% of our funding comes from RCUK and a further 15% from the EU. These summary figures however disguise a real trend – in 2012/13, RCUK (EU) funding accounted for 60% (22%) of total income, down (up) from 88% (1%) in 2008/9. Other contributions have come from UK Government (non-RCUK), UK charities and industry - notably £0.5M – £1M p.a. for the IAC (that is included in REF4b/c data of other UoAs). In addition to the £25.2M of research income-in-kind contribution

from BIS Research Councils quoted in REF4b/c, a further £10M was awarded for access to worldwide facilities, £6M of which was for observing time for the Astro group on the Chandra satellite (NASA), £2.25M for time on the Spritzer space telescope, £1.5M for access for CES members to high magnetic field facilities around the world, and £0.6M for access to the Spring-8 synchrotron in Japan (Dugdale).

Research Infrastructure and Resources

The University is investing £4M for refurbishment of the School with new offices and laboratory space, a new materials synthesis and characterization facility and a new UoB clean room. The project started in 2012 and includes a striking new entrance foyer and a major upgrade to the building's infrastructure.

The NSQI is a £11M research centre dedicated to supporting innovative projects from across the University. The Centre contains a wet lab, containment level-2 tissue culture rooms, class 1000 cleanrooms, as well as low and ultra-low noise labs. As anticipated, Physics has been the major user of the building from the start. As well as hosting the BCFN, nine of the basement labs have been in use by academics from the School (McMaster, Antognozzi, Miles, O'Brien, Oulton, Fox, Gersen, Schwarzacher, Royall). The stability and controllability of the research space is world-leading. Imaging at atomic scales, molecular motion and mechanical response at the nm and sub-pN level and detectable currents of a few pA are achieved routinely.

Work has commenced on the Bristol Nano-Fabrication Facility (BNFF) which will provide a state-of-the-art University-wide clean room facility for the fabrication of nanoscale devices and structures spanning a wide spectrum of research, including electronics, photonics, materials science, biological science and fundamental physics. The recently opened Materials Synthesis and Characterization Facility (MSCF) provides bespoke laboratory space for the preparation, synthesis and physical property characterization of both organic and inorganic crystalline samples. It contains a variety of furnaces (up to 1800C) as well as an infra-red image furnace (up to 2200C). The School also houses a X-ray diffractometer, a scanning electron microscope (SEM) and a SQUID magnetometer. Physics has also benefited from £8M University investment in a new machine room and BlueCrystal HPC computing over the period 2006-2012; members of the School being active in both its oversight and its management.

The CQP has been identified by the UoB as strategically important: for the University; for the local region and for the UK as a whole. Significant UoB support for the CQP has therefore been provided through the appointment of 2 administrative staff, a research manager, a project director and a programme manager. The UoB has also funded 4 PhD studentships, provided new and refurbished office and lab space and is establishing a £200k p.a. strategic develop-ment fund in line with the plans agreed to deliver on the scientific and impact roadmaps.

Associated with the IAC is a wide range of equipment (e.g. Auger, Focussed Ion Beam, Secondary Ion Mass Spectrometry) used to both synthesize and characterise thin films and surfaces. In collaboration with the NSM group, the IAC were recently awarded £400k for the procurement of a high-resolution SEM. Coupled with the School's unique capability in high-speed AFM, the SEM will anchor an internationally leading 'nano-imaging' facility of significant benefit to UK research where the observation of materials at the nanoscale is essential, contributing to advances in structural composites, semiconductors, energy generation and nanotechnology.

The CES group has a dedicated helium liquefier, several dilution refrigerators and helium-3 refrigerators as well as superconducting magnets up to 19 Tesla. They also have an angular correlation spectrometer with a cryo-cooled sample stage for positron annihilation studies. The MNM group runs an extensive reliability testing and failure analysis laboratory, thermographic imaging instrumentation and transmission electron microscopes (TEM) as well as advanced facilities for electrodeposition and electronic device reliability testing. Recently, the Group, in collaboration with the University of Oxford, secured £2.1M of EPSRC funding to purchase an aberration-corrected high resolution TEM combined with state-of-the-art microanalytical facilities to carry out elemental microanalysis with atomic resolution.

Physics has 12 FTE research and workshop technicians housed in a new £2M state-of-the-art mechanical and glass workshop suite that opened in 2009. Computer support is provided centrally,

with dedicated provision for the research programme of the PP group and the Astro group (Starlink) as well as a local Linux computer cluster. The excellent in-house School Library continues to provide comprehensive access to books and a wide range of periodicals and databases. During the summer of 2013, the library underwent a major investment including improvements to its IT infrastructure. There is also an Access Grid room within the Physics building. Finally, in the academic year 2012-13, over 100 seminars or colloquia were delivered within the School. These are complemented by a new Science Faculty colloquium series, launched in 2010, through which high-profile researchers are invited to present their groundbreaking work to students and academics from across the Faculty.

e. Collaboration or contribution to the discipline or research base

Internal collaborations: The School fosters interactions between research groups and with academics in other departments. Cross-departmental collaboration is facilitated through the Faculty Research Committee, while the Institute for Advanced Studies (IAS) Visiting Professor scheme funds distinguished overseas visitors and collaborators. Examples include:

- Recent articles in *Science* by O'Brien (CQP) and Popescu (TP) with Yu (EE), and by Miles and Antognozzi (NSM) with Woolfson (Chem) and Booth (Biochemistry).
- Joint BBSRC grants between Antognozzi (NSM) and Brady (Biochemistry) and between Gersen (NSM) and Banting (Biochemistry).
- NERC grant between Leinhardt (Astro) and Elliott and Walter (Earth Sciences) on planetary formation.
- The collaboration between Brook and Newbold (PP), Anderson (Geography) and Holcombe (Civil Engineering) in the application of Grid computing to landslide risk modelling for developing countries.
- Joint SARTRE/MRC grant (£0.5M) between Miles and Hoerber (NSM), Mumford (Haemotology) and Wiggins (Mathematics) looking at diagnostic probe array sensors for rapid and robust blood analysis.
- IAS Benjamin Meaker Visiting Professors were awarded to Geoff Pryde (Griffith University, Brisbane) and Yogesh Joglekaar (IUPUI, Indiana) who visited CQP in 2011 and 2013 respectively, to Luis Melo (Lisbon) who visited the NSM group in 2010/11 and to Derek Richardson (Maryland) who visited the Astro group in 2013.

National collaborations: Research staff also participate in a multitude of significant national collaborations as evidenced by joint funding awards in the examples given below:

- £6.2M EPSRC Programme grant between Kuball and Uren (MNM) and six other Universities in 'Silicon Compatible GaN Power Electronics"
- EPSRC Basic Technology Grant "NANOSCOPE: looking inside a living cell with nanoscale resolution" between Dennis (TP), Southampton and St Andrews.
- Joint EPSRC grant between Annett (TP) and Blamire's group in Cambridge on spin triplet pairing in superconductor-ferromagnet multilayer structures.
- The NSM and TP groups share a number of grants (e.g. £3.5M for the dynamic holographic assembler) and high-profile publications with Padgett (Glasgow).
- A £330k NIHR-i4i grant between Velthuis (PP), the UoB Hospitals Trust and Swansea, developing a novel sensor for beam monitoring for intensity-modulated radiotherapy.

International collaborations: The School participates in many international collaborations:

- Members of the PP group, actively involved in the CMS, LHCb and NA62 experiments being undertaken at CERN and leading various detector and physics working groups.
- Members of the Astro group are affiliated with many global-scale surveys, such as the XXL and GAMA surveys. The latter is a pan-European team awarded the largest-ever allocation of observing time on ESA's XMM-Newton satellite.
- EPSRC-JST Cooperative Grant in "Novel Quantum Matter in Correlated Oxides" between CES and TP group members and St. Andrews, Kyoto and Tokyo (£0.4M).
- The collaboration between Hussey and Carrington (CES) and Proust from the pulsed high magnetic field facility in Toulouse on cuprate superconductors has yielded 4 articles in *Science*, *Nature* and *Nature Physics* since 2008.
- The MNM group has established links with international companies including United

Monolithic Semiconductor, Texas Instruments, NXP and Selex and is a major player in European Defense Agency (MANGA), European Space Agency (GREAT), Office of Naval Research (DRIFT) and DARPA (NJTT) research projects.

- CQP are involved in a number of multinational projects including: DIAMANT, (Diamond based atomic nanotechnologies), PHORBITECH (development of an 'optical toolbox)', QUANTIP (development of the next generation of integrated quantum circuits), BBIO (development of a multifunctional integrated silicon photonic platform) and a Marie Curie Training Network on Integrated Quantum Photonics (PICQUE).
- Members of the IAC are involved with the ALFRED2 fast reactor programme to develop a Gen IV fission reactor system based on molten lead as the coolant.

Influence: Influence is evidenced by the following awards and contributions to the discipline:

- Miles was elected a Fellow of the Royal Society (FRS) in 2011 and a further five FRSs (Berry, Enderby, Evans, Nye and Steeds) remain active within the School. The School also hosted five Royal Society Wolfson Research Merit Awards (Miles, Hayden, Hussey, O'Brien and Popescu), an ERC Advanced Grant (Popescu), an ERC starter grant (O'Brien) and three ERC Consolidator Grants (Rademacker, Royall and Thompson).
- The School currently hosts 1 Royal Society URF (Short), 1 STFC Advanced Fellow (Leinhardt), 1 RAEng Fellow (Peruzzo), 2 Leverhulme Fellows (Matthews and Gradhand), 2 1851 Royal Commission Fellows and a number of Marie Curie and Royal Society Newton International Fellows.
- O'Brien has been awarded the 2013 IoP Bates Prize, the 2011 Daiwa Adrian Prize, the 2010 Optical Society of America Adolph Lomb Medal 'for seminal contributions to quantum optics, optical quantum metrology and quantum information', the 2010 IoP Moseley Medal and the 2010 International Union of Pure and Applied Physics (IUPAP) Prize in Atomic, Molecular, and Optical Physics. In 2008, he was elected to the Global Young Academy and is a Fellow of the American Physical Society.
- Popescu received the 2011 Bell Prize "for his enormous contributions to quantum mechanics" and holds a Distinguished Research Chair at the Perimeter Institute.
- Evans has been awarded the 2014 European Physical Society Liquid Matter prize.
- Kuball was awarded the 2010 He Bong Kim Award of CS-Mantech.
- Miles is Chief Scientific Adviser to the IoP publishing house and a member of the REF 2014 Physics sub-panel (UoA9). Both Miles and Hussey served on EPSRC Strategic Advisory boards (Nanotechnology and Grand Challenges in Physics respectively).
- Worrall became President of the International Astronomical Union (IAU) Division for High Energy Phenomena and Fundamental Physics, while Birkinshaw is Chair of the STFC's CTA oversight committee and the UKSA's Planck oversight committee.
- Goldstein has chaired the STFC Particle Physics Grant Panel (Experimental) since 2011. Brook chaired the STFC oversight committee for the ALICE project (2003-2009) and was a member of the LHCb physics-planning group. Newbold and Rademacker are Deputy Chair and member of key STFC panels (PPRP and PPAP) respectively.
- During the REF period, academics from the School have given over 400 invited talks at national and international conferences and workshops. Highlights include: Hussey giving the annual Mott Lecture at the 2011 IoP Condensed Matter and Materials Physics conference, Birkinshaw the lead-off speech at Special Session 2 of the IAU General Assembly 2012 in Beijing, O'Brien giving over 40 keynote lectures including SPIE 2013, CLEO and CLEO-Europe (Conference on Lasers and Electro-optics) 2013. He has also spoken at the World Economic Forum and the Bristol TEDMED Conference. Berry has given a number of distinguished lectures, including the Hamilton lecture, Princeton, the Bernoulli lecture, Groningen, the inaugural Chia-Chiao Lin distinguished lecture, Tsinghua, Beijing and the Ramanujan Lecture, Saha Institute, Kolkata.
- The School engages extensively on an editorial level with a number of journals including: *J. Mater.Sci.* (Seddon), *J. Mod. Phys.* (O'Brien), *J. Optics* (Dennis), *J. Phys. A* (Berry), *Monthly Notices Roy. Astro. Soc.* (Worrall), *Nanotechnology* (Miles), *Nano Today* (Miles), *New J. Phys.* (Hussey), *Optics Express* (Dennis), *Optics* (O'Brien), *Polymer* (Miles), *Proc. A Roy. Soc.* (Berry) and *Thermodynamics* (Short). O'Brien is the founding Editor-in-Chief of *Technologies*.