INTERNATIONAL PERCEPTIONS *of* UK RESEARCH *in*

PHYSICS *and* ASTRONOMY

EPSRC

Engineering and Physical Sciences Research Council

PPARC

Institute *of* Physics

FOREWORD

This study is the second in a series aimed at providing international commentary on core fields of the United Kingdom's science and engineering research base. The first study in the series was that of the Royal Academy of Engineering and the Engineering and Physical Sciences Research Council (EPSRC) entitled International Perceptions of UK Engineering Research.

The Review arose from the interest of the Office of Science of Technology (OST) in receiving an international assessment of the standing of British physics research and the Research Councils' wish to obtain a better understanding of the strategic position of the subject, as perceived by international experts. The Institute of Physics and the Royal Astronomical Society, as representatives of the scientific research community, were keen to ensure that any such review would be undertaken with rigour, accuracy and sensitivity. All four sponsors agreed that, in order to be useful, the Review must command the respect of the research community.

Accordingly, the Review was initiated under the sponsorship of the Engineering and Physical Sciences Research Council (EPSRC), the Particle Physics and Astronomy Research Council (PPARC), the Royal Astronomical Society (RAS) and the Institute of Physics.

The Terms of Reference of the Review were: To report on the standing, balance and potential of physics research in the UK, and provide a comparison with physics research internationally. The Study covered all Science Budget physics research undertaken by, or for, the UK Research Councils in universities, central laboratories and participation in, and use of, international facilities.

The Review was overseen by a Steering Group comprising:

Professor Sir Gareth Roberts FRS (Chair), President of the Institute of Physics
Professor David Williams, President of the Royal Astronomical Society
Professor Richard Brook, Chief Executive, EPSRC
Professor Ian Halliday, Chief Executive, PPARC

The Institute of Physics provided the Secretariat for the Steering Group and the International Panel: Peter Cooper (Director, Science), Philip Diamond, Alwyn Jones, William Nuttall, Tajinder Panesor and Ursula Wielgosz.

The Steering Group was advised by an Advisory Group selected by the Steering Group and drawn from the corresponding communities of the four sponsoring bodies. The Advisory Group was a 'virtual community' in that it never met in person. Its discussions and advice were developed and disseminated electronically. The Advisory Group advised upon the full range of materials to be prepared for the International Panel. These materials are described in Appendix A.

The International Panel, from left to right:

Alexander M. Bradshaw, Jürgen Mlynek, Stephen R. Forrest, Marcel Goossens, Richard Casten, Daniel Kleppner, David Gross, Roger D. Blandford FRS, Jean-Jacques Aubert, David Ceperley, Jürgen Kirschner

The membership of the International Panel was determined by the Steering Group. The principal criterion shaping the composition of the International Panel was that the sub-fields of physics should be covered as fully as possible. The Panel comprised:

Professor Alexander M. Bradshaw, Max-Planck-Institut für Plasmaphysik, Garching, Germany (Chairman)
Professor Jean-Jacques Aubert, IN2P3, Paris, France
Professor Roger D. Blandford FRS, California Institute of Technology, USA.
Professor Richard Casten, Yale University, USA.
Professor David Ceperley, University of Illinois, USA.
Professor Stephen R. Forrest, Princeton University, USA
Professor Marcel Goossens, Katholieke Universiteit Leuven, Belgium.
Professor David Gross, University of California Santa Barbara, USA.
Professor Jürgen Kirschner, Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany.
Professor Daniel Kleppner, Massachusetts Institute of Technology, USA.
Professor Jürgen Mlynek, Universität Konstanz, Germany

The Steering Group is very grateful to the International Panel, and especially the Chair, Professor Alex Bradshaw, for the time committed to the Review, and the conscientious and thorough approach taken to the work. The result will be important to all the sponsors in helping to shape their future strategies for the support of physics research in the UK. The report is commended to the British physics community for its consideration and comment.

Professor Richard Brook	*Chief Executive, EPSRC*
Professor Ian Halliday	*Chief Executive, PPARC*
Professor Sir Gareth Roberts FRS	*President, The Institute of Physics*
Professor David Williams	*President, The Royal Astronomical Society*

EXECUTIVE SUMMARY

Physics (including astronomy) is an integral part of our culture, providing the foundations for many scientific disciplines including chemistry, biology, the geo-sciences and engineering. The increase in wealth, economic globalisation, living standards and the quality of life in the twentieth century has been largely based on technological progress which in turn has relied heavily on innovative research in physics. These trends are anticipated to continue and, indeed, strengthen in the 21st Century.

The case for supporting physics research on a broad basis is, therefore, overwhelming. In view of the importance of technological innovation, it is the conviction of the Panel that there must be adequate funding of all aspects of physics if the UK is to continue to hold its place as a leading nation in the world's economy. Furthermore, great care must be taken to marshal the United Kingdom's human resources: there is little doubt that attracting and maintaining the best minds in the country to the field of physics is an essential ingredient to the overall success of these endeavours.

The Panel is of the opinion that:

- At its best, research in physics and astronomy in the UK is at the very highest level world-wide.

- Beneath the peaks of scientific excellence, however, UK physics research quality noticeably drops, largely due to a lack of adequate resources. For similar reasons, there are deficiencies in the breadth of coverage of some important sub-fields. As a result, the potential for seizing new opportunities and for maintaining the UK's

overall excellent standing in international physics and technology research may be impaired.

- Condensed matter physics still maintains a substantial research base with some examples of world-leading work. Nuclear physics has secured international strength by a judicious focussing of scarce resources. There have been missed opportunities in atomic and molecular physics, although in some areas of this sub-field UK leadership is apparent. The strength of particle physics and astronomy/astrophysics is supported and ensured by the strong international collaboration appropriate for these sub-fields.

- Physics research in the UK continues to suffer from a low level of funding. In fact, the field is currently in a state of slow recovery from a long period of chronic under-funding. Substantial increases are now required in order to bring UK physics research up to international levels. Insufficient funding has caused the UK to miss important areas of opportunity. In particular, research infrastructure (both equipment and human resources) has been in decline for many years and may be reaching a critical point. Urgent action is required to reverse this trend.

- Efforts must be made to attract and retain young people in physics research and education – this is a task for both the physics community and government. In particular it is essential to attract more physicists into careers in school teaching, especially in state schools. Moreover, there is a need to increase the fraction of women taking undergraduate physics courses and to facilitate their retention at all levels in the profession.

- Serious attention must be paid to enhancing the career development of young physicists. The existing salary structure is not internationally competitive and is a significant disincentive. The creation of long-term research positions in universities should be encouraged in order to avoid the current situation whereby many physicists are trapped in a series of successive short-term, low paid appointments.

- The UK's ongoing support for international facilities is a vital contribution to its scientific strength. It is important for the UK both to participate in developing and operating such facilities and to be able to have sufficient access to them for experimental research. The Central Laboratories should also continue to play an important role in major physics projects, both on and off-shore.

- The UK should participate in the development of new knowledge (and, indeed, in its utilisation for wealth creation) by giving physicists the opportunity to follow their scientific instincts in research. Managed programmes should be used by the Research Councils with restraint. The Research Councils should encourage more interdisciplinary research and fund innovative proposals from young people. Several UK research policies, in particular those regulating postgraduate education, seem excessively rigid and formulaic.

1. INTRODUCTION

1.1 TERMS OF REFERENCE

The Panel interpreted its task as a short, but intensive study of UK research in the broad fields of astronomy and astrophysics, atomic and molecular physics, condensed matter physics, nuclear physics and particle physics. Since the Panel lacked expertise in several sub-fields, in particular, biological physics, medical physics and geophysics, it was unable to comment on these research areas. The Panel also felt that the Terms of Reference as given by the Steering Committee, namely, 'to report on the standing, balance and potential of physics research in the UK, and provide a comparison with physics research internationally', required further definition.

The Panel interpreted 'standing' to mean the quality of physics research in the UK compared to other countries, in particular to those of similar size and comparable science budget. The determination of research standing considered both current work and that undertaken in recent years.

The Panel decided that it would not be possible to comment on the relative sizes of different physics research sub-fields ('balance') within the UK, i.e. to determine what mix of emphasis between sub-fields is objectively appropriate or optimal. Nor did the Panel wish to imply that any country achieves such an optimal mix even if it could be defined. It was felt that each country's distribution of research activity reflects local circumstances such as history, political priorities, industrial

strengths, and that these factors combine with random circumstance and serendipity to generate the national mix in each case. Moreover, the Panel noted that independent of these issues, it had neither the resources nor the time to approach such a question with the rigour that it would necessarily require. The Panel did conclude, however, that it could comment on the prominence of a given sub-field in the UK compared with that observed in other comparable countries. The Panel therefore interpreted 'balance' internationally by sub-discipline, rather than nationally across or between sub-disciplines.

The Panel understood 'potential' in this context to mean the way in which the future of physics and astronomy in the UK is assured. The most important factor affecting the future development of physics research in the UK is human potential. Other factors include investment in infrastructure and possibly large-scale facilities. The Panel decided to address these issues specifically.

1.2 INPUT DATA

The study was able to draw upon five sets of input data:

Experience and knowledge of UK research and of the British physics and astronomy communities by the Panel members in their areas of expertise.

A substantial body of data on the funding, staffing and outputs of physics research throughout the university and research council sector collected by the Secretariat (see Appendix A).

Site visits to six universities (Cambridge, Glasgow, Manchester, Oxford, Queen Mary and Westfield College London and Sheffield) and to CLRC Rutherford Appleton Laboratory. The programme of visits for the Panel was drawn up by the Steering Committee and agreed to by the International Review Chairman.

The results of a survey sent to about 150 colleagues outside the UK. The questionnaire is reproduced in Appendix B. No quantitative summary was attempted, the main purpose being to give Panel members a broader base for the views expressed.

Bibliometric analyses. The Panel had access to three sets of bibliometric data (see Appendix A) but was acutely aware of the limitations of this methodology. In addition, there was concern that bibliometric research required extended investigation of the data sets concerned and was therefore not well suited to interrogation during a one week review of this type.

Despite the substantial body of input data the Panel's direct contact with UK physics was very brief. Moreover, of the five days the Panel spent together in the

UK, half the time was taken up with the visits. The Panel felt that six university physics departments and one central facility were the very minimum for such a programme of visits. However, an additional day for discussions would have been very useful, in particular for making more use of the expertise of the Secretariat and the information it collected. This observation might be useful for future such exercises in other disciplines.

1.3 CAVEAT

The Panel realises that it may harbour some misconceptions about physics in the UK and, on several points, even be ill-informed. On the other hand, it would have been necessary to spend a substantially longer period in the UK in order to carry out a comprehensive 'evaluation'. The Panel doubts, however, whether such an exercise would have led to substantially different conclusions than those presented here. Nonetheless, the description 'perceptions' in the title of the Report – borrowed from the engineering study – is apt.

Despite any shortcomings the Panel hopes that its Report has the particular strength of international perspective and independence. Moreover, it hopes that the Report will be useful and will find a place in the range of inputs that shape UK research policy in physics.

1.4 ACKNOWLEDGEMENTS

The Panel wishes to thank the Steering Group for the preparatory work and for the important discussions on the Terms of Reference. It is greatly indebted to the members of the Secretariat for the excellent scientific and logistic support; without their enthusiastic help the whole exercise would not have been possible. Further, the Panel would like to express its thanks to the university departments and the CLRC who received the Panel for the visits and provided considerable information and documentation.

2. FINDINGS ON THE SUB-FIELDS OF PHYSICS

2.1 ASTRONOMY AND ASTROPHYSICS

The Panel concluded that the UK enjoys an extremely high standing in both astrophysics and solar physics. The very best departments deserve their RAE rankings and have maintained their international reputations while others have grown in stature over the past decade. Many individual researchers, working in smaller departments, are regarded as leaders, internationally, in their areas of specialisation.

In recent years, the emphasis of UK astrophysics has been on extragalactic/cosmological research and high energy astrophysics with theory/phenomenology being especially prominent. UK astrophysicists have been leaders in many active sub-fields including the analysis of microwave background fluctuations, numerical simulations of the growth of large scale structure, galaxy formation, galactic structure, stellar formation and evolution, the intergalactic medium, gravitational lenses, pulsars, active galactic nuclei, x-ray binaries, cataclysmic variables, gravitational radiation and the interpretation of gamma ray bursts. The situation is similar in solar physics where UK researchers also have a world-leading role in many active sub-fields including helioseismology, dynamo theory, magnetoconvection, coronal activity, reconnection and magnetohydrodynamic waves. As well as being of importance in its own right, solar physics will continue to feed key ideas on the behaviour of fundamental processes into many areas of astrophysics. Indeed, the vibrant strength of solar physics and its close relation with astrophysics is one of the strengths of the UK in this sub-field. Active research areas, where UK researchers have been less prominent, include extra-solar planets and plasma kinetic theory as applied to the sun.

In addition to its established optical-infrared telescopes sited in the Canary Islands, Hawaii and Australia, the UK jointly operates a sub-millimetre telescope JCMT and the multi-element radio-link interferometer, MERLIN which are both unique facilities. Looking to the future, the UK has a significant investment and a large role in the US-led Gemini 8m optical telescopes, is constructing a 4m optical-infrared survey telescope, VISTA, and plans to participate in the millimetre interferometer ALMA. These are all excellent projects.

There is a strong involvement with many space observatories (astronomical, solar and space physics) both instrumentally and observationally through guest investigator programmes for which UK proposals are relatively successful. Current UK investigators also play an important role on several solar and space physics observatories. The UK will collaborate on the Japanese-led Solar-B, the NASA STEREO mission, ESA's combined far infrared-microwave-background mission, FIRST-Planck, and the Next Generation Space Telescope, and hopes to participate in several proposed missions including the astrometric telescope, GAIA, the gravitational wave observatory, LISA, and the optical interferometer, Darwin.

Numerical simulation is playing a more prominent role in both astrophysics and solar physics and UK scientists have international prominence in this area. Recent hardware initiatives are providing good research opportunities which are being exploited.

The rate of readily communicable, astronomical discovery remains very high and UK astronomers have been at the forefront of efforts to improve the public perception of physical science and to communicate to academically promising schoolchildren the diverse benefits and opportunities that derive from a physics or engineering education. The Panel felt that these outreach efforts had been relatively effective with schoolgirls and young women, who are otherwise under-represented in university physics courses.

However, despite this positive endorsement of the state of UK astrophysics and solar physics, the Panel points out that important challenges lie ahead. As most discoveries are multi-national in character and no country can afford to take up all the opportunities available, long-range choices will have to be made in order to maintain the high level of research excellence that the UK has historically enjoyed. Some observations in this respect include:

The support of ground-based observing appears to be at a lower level than in many other European countries, Japan and the US. In particular, the access to 8/10m class optical-infrared observing facilities through Gemini seems too low to sustain a balanced research program, on which theory and phenomenology is crucially dependent. In addition, observational radio astronomy, a field pioneered in the UK, is now mostly prosecuted abroad. Possible remedies, that deserve serious consideration, include participating in the VLT and ALMA through the European Southern Observatory (ESO) and upgrading MERLIN to a fibre-linked array. In solar physics, it will be necessary to participate fully in the next generation of space missions.

Although there are excellent astronomical instrumentation groups, it is questionable whether the depth of staffing and the general infrastructure are sufficient to allow the UK to participate at an appropriate level in future international projects such as a proposed 30m class European optical/infrared telescope. Astronomical instrumentation requires effective and mutually beneficial collaboration between academic research and industry.

Frontline astronomical research is increasingly centred around very large observational databases and sophisticated simulation. Computing facilities will have to be continuously upgraded to remain competitive. For example, in solar physics the computing power will have to improve by a large factor to match the expected gain in spatial and temporal resolution of the observations over the next decade.

The paucity of observing opportunities on major telescopes, low salaries and perceived poor career prospects are leading many of the most promising and ambitious, young researchers to either leave the field or the UK.

In summary, the standing of UK astrophysics and solar physics is very high with the balance currently tilted towards theory/phenomenology. The scientific potential of the field as a whole is enormous, but may only be realised in the UK if there is further, targeted investment in ground-based astronomical observing and space physics, in infrastructure, which will ensure an important role in international projects, in computing and in support of the best younger researchers.

2.2 ATOMIC, MOLECULAR, OPTICAL AND PLASMA PHYSICS

The UK has a strong tradition in spectroscopy, atomic and molecular theory, and in collisions. However, atomic physics has undergone a revolution due to the advent of laser cooling and trapping techniques, the development of atom optics, the creation of atomic Bose-Einstein condensate, and the creation of short pulse light sources. The UK is perceived to have largely ignored these developments in favour of its traditional interests. Consequently, in comparison to former times when the UK was recognised as a leader and innovator in atomic and molecular physics, the work now is regarded as largely derivative.

Nevertheless, as one might hope, there are some exceptional areas where UK leadership is recognised. These include quantum chaos and wave theory, quantum cryptography, atoms in strong laser fields and astro-chemistry. Two groups have gained recognition in cold atom research. These bright spots shine all the more conspicuously in view of the general perception that atomic and molecular physics in the UK has slipped from its role of leadership.

The Panel observed that in experimental quantum optics (in the narrower sense of the word) there is only a little activity going on. Research directions like cavity-QED, non-classical states of light or quantum non-demolition measurements are underdeveloped. On the other hand, theoretical quantum optics is of very high standing, although this field is found only at a few universities.

Quantum information and quantum computation as a very recent field is very successfully pursued from the theory side: here the UK is at the forefront. From the experimental side, apart from pioneering work in quantum cryptography, activities using, e.g. ion traps, have just started. It should be noted that quantum information technology is a good example of interdisciplinary research at the boundary of optics, atomic physics and solid state physics with a strong link to computer science. The UK is in a good position to build up further strength in this future-oriented research.

Modern optics including non-linear optics, fibre optics and laser physics have a high international standing, with pioneering contributions in e.g. the creation of femto-second laser sources and novel tunable solid-state lasers. New optical materials like photonic band gap materials are studied at several places in the UK with important results of international visibility. In contrast, opto-electronics still has a weak base, at least in UK physics departments.

In recent years the Vulcan laser at RAL has become one of the most important high-intensity laser facilities worldwide; a number of first-rate results have been obtained.

It should be noted that major countries all over the world consider photonics and optics as key technologies of the future. As a consequence, it can be assumed that other countries will fund optics at a very considerably increased level in the future. In this context, the UK should try to keep up its strength in this promising research area.

High temperature plasma physics (fusion research) in the UK has profited greatly from the presence of JET on the UKAEA Culham site which despite being a European facility has always had a high percentage of British staff. The UK's own (magnetic) fusion research centre in Culham is small in comparison to the efforts in Germany, France and Italy; a new spherical tokamak has just been commissioned, an area in which the UK is a world-leader. Neither facility is formally covered by the present Review, but about ten active UK university groups are involved to various extents in activities at Culham. Due to the availability of the Vulcan laser at RAL several outstanding experiments on laser-plasma interactions have recently been carried out by productive university groups. Low temperature plasma science recently went through a period of decline in the UK, but now seems to be recovering due to new blood and to industrial interest in plasma technology. The Panel noted, however, that equipment and infrastructure remain poor in comparison to Germany and France.

2.3 CONDENSED MATTER

As an overall assessment of condensed matter physics in the UK, the Panel found that the effort is comparable to the best efforts in Europe (notably Germany), although it lags behind Japan and the US. In a few areas, the work is well ahead of comparable efforts

anywhere, but there also appear to be significant areas which are largely unexplored. The Panel's assessment is that the quality is high, but that the coverage of this broad subject is non-uniform, and the UK's overall ranking is in danger of slipping.

There is no question that the overall research quality in condensed matter can benefit from closer collaboration between disciplines, particularly with engineering and chemistry. However, the Panel found little evidence for a well developed tradition of interdisciplinary collaboration such as has benefited countries like the US.

Among the highlights the Panel noted the following:

Work in polymers and polymer opto-electronics is absolutely first rate, leading the world's effort. The research at some universities has achieved the highest levels of international recognition. Lack of strong interactions with chemistry departments may prevent these centres of excellence from having a broader nationwide influence.

Excellent work can be found in magnetism, in particular thin films, dimensionally reduced systems, applications of circularly polarised synchrotron radiation and transmission electron microscopy. The emerging field of magneto-electronics is recognised but not yet taken up fully. In general, there are excellent groups, however few, against a background of much lower quality.

Work in low temperature physics and superconductors also has achieved a very high level of international visibility.

In the middle range of excellence are efforts in theory and semiconductor physics. Over the last 20 years the UK has been a leader in computational physics, particularly in parallel computing and numerical analysis. It is expected that computational methods will become even more important in many, if not most fields of physics. Given the rapid change in the hardware and software environment, continued attention needs to be given to developing and implementing a strategy for renewal of computational facilities. The Panel identified problems connected with access to such facilities; for example, access to CSAR is not coupled to research funding of postdocs and favours large collaborations over individual investigations.

It was the opinion of the Panel that some work in III-V semiconductor growth and structure is highly regarded and has made significant contributions to the community. Again, increased collaborations between physics and engineering throughout the UK could greatly expand the world-wide presence of UK physics in this rapidly growing field.

The Panel found that UK work in surface science is not very strong, but a few examples of excellence were nevertheless apparent. The Panel noted that this subject suffers from being located in physics at some universities, and in chemistry at others. There are, however, some good examples of inter-departmental co-operation.

One potential weakness is found in the area of molecular and nano materials. These fields are growing in importance around the world. The UK physics community must take a proactive role in identifying and supporting such rapidly developing areas in condensed matter, or it could miss opportunities which have the potential for wealth generation and new and exciting science.

The Panel noted that the Daresbury synchrotron radiation source and ISIS play an increasingly important role in the development of condensed matter physics both in the UK and world-wide. The importance of these facilities (and, indeed, of the planned next generation synchrotron radiation source) will increase dramatically as the emphasis of the field continues to shift further into the study of soft (e.g. organic and biological) materials.

2.4 NUCLEAR PHYSICS

The Panel felt that experimental nuclear physics in the UK had reinvented itself, following the closure of the Daresbury Tandem facility. Many people anticipated a rapid demise of the field in the UK following the shutdown of what was, at the time, the premier facility of its type in the world. Instead, the community regrouped, with the injection of new blood and enthusiasm, to build up a world-class level of research in certain, focused areas without benefit of a domestic facility. The Panel agrees with several respondents to the questionnaire who commented that this has been remarkable.

As before, the principal UK focus lies in nuclear structure and nuclear astrophysics. UK university groups and the Daresbury group have emerged to play key roles in instrument and detector development, data acquisition technology, experiment, and physics interpretation at a number of the best off-shore facilities such as Jyväskylä, GANIL, Louvain-la-Neuve, Argonne, Strasbourg, Oak Ridge and TRIUMF.

With the advent of the technological capability to separate, accelerate and study exotic nuclei far from the valley of stability, UK nuclear physicists are complementing their traditional focus on high spin states, superdeformation, magnetic rotation and the like, by taking on leading roles in such areas as nuclear astrophysics (energy generation in stars, breakout from the CNO to the rp cycles, nucleosynthesis), proton emission at the proton drip line, loosely bound quantal systems, exotic shell structure, and the study of enhanced effects of T=0 interactions in N=Z nuclei at first-generation exotic beam facilities. These groups are poised to help lead the way when advanced next-generation facilities come on line.

Only small UK efforts exist in other areas of nuclear physics, such as medium energy electron scattering and relativistic heavy ions, although the few groups involved are making significant contributions. Nuclear theory in the UK is modest with local efforts in reaction theory, clustering phenomena, and halo nuclei. Academic research in applied areas, such as nuclear waste studies, is essentially absent.

Thus, UK nuclear physics is concentrated in a few areas, rather than distributed over the whole field. Such a concentration is appropriate, given the limited scale of funding compared to countries of comparable size and economic level, since it does enable the UK to have major impact in key forefront activities, while necessarily foregoing other active areas of current research.

A challenge and opportunity for the future lies in the question of an on-shore exotic beam facility, SIRIUS, at RAL. Timely construction would give the UK the first advanced ISOL radioactive beam machine in the world and make the UK the world centre for work at this new frontier for a decade or more. Indeed, even when the US 'RIA' facility is built, these two centres would be complementary and, between them, not nearly satisfy the world-wide demand (~2000 scientists) for exotic beams for nuclear and astrophysics, fundamental studies, and medical and industrial applications.

2.5 PARTICLE PHYSICS

2.5.1 *EXPERIMENT*

Overall, the UK participation in particle physics is first class, with British physicists taking a leading role in many collaborations. Their overall contributions compare well with other European countries. Were the funding situation, which has been much worse than in France, Italy or Germany, to improve, they would be able to restore the technical support for the university groups and strengthen their involvement in particle astrophysics, which is not comparable to other European countries.
UK experimental particle physics is spread over 16 Physics departments and RAL and is engaged in most of the international programme.

At CERN, after strong participation in the LEP experiment, they are deeply committed to the Atlas and CMS detectors under construction for the LHC. The UK groups have made major contributions to the design R&D of these detectors and are now responsible for substantial parts of their construction. The LHCb detector, dedicated to studies of B physics and to accurate measurements of CP violation, has strong support from UK groups. They are responsible for major parts of the detector construction.

At DESY in Hamburg, there is a strong participation in the ZEUS and H1 experiments, which study e-p collisions at an energy of a few hundred GeV in the centre of mass. Currently they are heavily involved in the analysis of the data from these experiments.

UK groups are involved in many experiments in the US. At SLAC, after participating in the SLD, they are deeply involved in BaBar, a dedicated experiment for measuring CP violation in B physics. They also participate in two major experiments at FNAL (CDF and D0) where they are attempting to find a low mass Higgs meson. The observation of neutrino oscillations represent the first sign of physics beyond the Standard Model. The UK is active in this field with a low energy neutrino approach (Karmen) and a long base line high energy neutrino experiment (MINOS) in the USA. There is a strong R&D

programme studying the design of an intense neutrino beam using a muon storage ring.

The support for particle astrophysics is split between particle physics and astronomy. A large national effort to detect dark matter is being pursued at the Boulby mine. Here the UK is competing with the best groups in the world and developing new ideas to improve the sensitivity of the experiment.

The UK is also involved in CRESST, in SNO for solar neutrino studies, and in ANTARES. UK physicists belong to the major initiators of the AUGER project.

The commitment of RAL and UK university groups to the technological aspects of large experiments gives them a strong position in the development of frontier technology. In Europe they play a leading role in grid computing, which could well be of critical importance.

2.5.2 *THEORY*

Elementary particle theory in the UK is relatively healthy with an adequate effort in phenomenology, a strong community of lattice gauge theorists and world class contributions to string theory and relativity.

Particle phenomenology in the UK is strong in some areas (higher order electroweak processes) but largely derivative. There has been relatively little activity on the exploration of physics beyond the standard model such as supersymmetry, extra dimensions and so forth. Given the large investment in experimental particle physics additional investment will be required to provide the theoretical support to the planned experiments at the LHC.

The UKQCD is a world class collaboration that has made important contributions to the study of lattice QCD. To maintain a leadership role in this activity, substantial investment in Teraflop computers will be required, perhaps in collaboration with Europe.

The UK has had a long history of leadership excellence in string theory and general relativity. British theorists have played a leading role in many of the recent exciting developments in non-perturbative string theory and M-theory. Care must be taken to preserve this area of excellence, especially in providing opportunities for young researchers in this field. Here and elsewhere, the UK will find it hard to maintain excellence unless it can provide opportunities for its best young people.

3. GENERAL FINDINGS ON PHYSICS IN THE UK

3.1 PHYSICS AND WEALTH CREATION

The economic well being of the United Kingdom today rests to a large extent on technologies that are the dividend from past investments in basic research. Evidence for this is abundant. The computers that made possible the information revolution are the payoff from early studies in semiconductor science; the communication revolution that is transforming the modern world is among the many payoffs of the laser – the laser grew out of studies on molecular structure; magnetic resonance imaging (MRI) originated from early research on atomic nuclei; the origins of the global positioning system (GPS) can be traced to early studies of general relativity. Broad investments in basic research in physics have returned dividends unimaginable at the time the research was performed.

There is every reason to expect that new technologies will continue to be created in the decades to come and that basic research in physics will continue to pay off in the new industries that they create. Furthermore, the research can be expected to provide new knowledge and techniques for all of the other physical sciences, and for the biosciences and biotechnology. Thus, the Panel believes that the health of physics is crucial to the well being of the United Kingdom.

To maintain its economic position, the UK must participate in the development of new knowledge by excellent scientists who are free to follow their scientific instincts.

3.2 HUMAN POTENTIAL: YOUNG PHYSICISTS

The Panel noted that first degree and PhD outputs in physics have remained remarkably constant in the last 14 years despite demographic variations. This indicates that physics has not lost its excitement and intellectual appeal for many young people. The International Panel notes, however, that physics has not experienced the multi-fold increase in undergraduate student numbers enjoyed by many other subjects. Concern was also expressed by the UK physics community that the level of attainment in maths and physics by first year intakes in recent years has declined. The transition to a four year degree course (MPhys/MSci) thus seemed to be a necessary development in this context, as well as enabling British physics graduates to compete more effectively for jobs in the wider European environment where undergraduate courses are usually longer.

The Panel noted the increasing number of physics graduates and PhD's – in fact, some of the very best – who give up careers in basic and applied science to work in other, often better paid professions. It is vitally necessary that a sufficient number of the best physicists trained in the UK remain within the heart of the subject, in order to:

- Provide the physics-based industry in the UK with well qualified young people.

- Secure the intellectual and human potential required for exploiting new discoveries via high-technology start-up companies.

- Provide sufficient physics teachers in schools (see below).

- Replace the approximately one third of the academic staff in university physics departments that will be retiring in the next ten years.

The outflow of talented people from physics – whilst extremely beneficial for the fields into which they go and demonstrative of the high levels of applicable skills gained from a physics training – is a cause for concern. It must be addressed by the whole UK physics community. An essential step in retention of the very best minds in physics would be to increase the salaries of research students, post-doctoral fellows and young academic staff to make them more competitive on an international scale (and, indeed, more competitive with other professions outside the university sector). Given the global nature of science and technology, the current large discrepancies between domestic and international pay scales has led to a damaging drain on intellectual resources in Britain.

The fact that tuition fees for foreign research students are substantially higher than those for UK or EU citizens is an unnecessary barrier to the attraction of the best young minds from abroad to UK PhD programmes.

3.3 HUMAN POTENTIAL: PHYSICS IN SCHOOLS

Attracting a diverse and highly qualified student population must start at the primary and

secondary school levels. One of the most worrying statistics brought to the attention of the Panel is the recent drastic decline in the number of physicists entering post-graduate teacher training courses. This may reflect the poor salaries and increasing administrative loads in the teaching profession, in particular in state schools. If so, urgent action is required. The importance of maintaining the supply of young, enthusiastic and well-qualified teachers cannot be underestimated.

The Panel noted that University academic staff are both motivated and expert in articulating the attractions and importance of a physics education. The Panel encourages them to be more proactive in working with the community at large and the schools to establish an early interest in young people for a career in physics.

3.4 HUMAN POTENTIAL: WOMEN IN PHYSICS

The Panel was presented with data that showed the fraction of female first year undergraduates was only one in five, lower than in other fields of science. This represents a significant, unrealised potential. A co-ordinated outreach effort directed at 12-14 year old schoolgirls is well worth supporting in attempting to redress this balance. In addition, the fraction of women employed in physics falls with career stage to one per cent at the professorial level. It is equally important to address and take steps to facilitate the retention of qualified women within the community of physicists.

3.5 UNIVERSITY INFRASTRUCTURE

The Panel interprets infrastructure to mean those aspects of research support that provide or expand research capacity. There must be mechanisms to support the long-term research needs of a department which are not motivated by the needs of any one particular project. Examples of such infrastructure include:

- Professional research support staff with experience and skills beyond those required of a single research project. Such human infrastructure requires long-term support to be fully effective and to maintain a high departmental morale.

- Modern high precision equipment in mechanical workshops supporting a broad base of research goals.

- Well qualified technicians

- Communications infrastructure, including networking and co-ordination of research information technology infrastructure and access to a broad base of primary research literature.

- Facilities for generic materials characterisation, including electron microscopy, x-ray diffraction, scanning probe microscopy, chemical analysis, etc.

The Panel was concerned that there may be serious infrastructure deficiencies in UK physics departments. It had the impression that the infrastructure situation is worse than in other, comparable countries and noted that the provision of the Joint Infrastructure Fund (JIF) had not alleviated this problem. On the contrary, some academic staff felt that this money is not being granted for infrastructure in the sense understood by the Panel, but rather for *new* items of research equipment. The Panel concluded that a particular outcome of JIF was to enable an increase in the number of research projects while doing little to ensure that existing research strengths and future ideas, as yet unimagined, are underpinned by the pre-requisite capacity.

The Panel noted that physics departments employ resourceful and talented people on both the academic and technical staffs. It appears that for too long the British system has drawn on such talents in order to maintain at a minimal operational level often obsolescent and worn-out equipment. Importantly UK universities facing such difficulties nevertheless manage to produce scientific results of the highest quality. The Panel suggests, however, that this capability cannot be maintained for much longer unless the infrastructure shortfall is addressed soon.

The Panel also observed a steady decline in non-academic support staff at both technical and administrative levels. It attributed this decline to a consistent reduction in resources and uncompetitive salaries with the non-academic sector. As the retention and attraction of high quality support staff is organic to the success of excellence in research, the Panel suggests that this problem be addressed to stem the continual decline of the human dimension of the research infrastructure.

Finally, to replace worn out or obsolete equipment directly associated with particular individual research programmes, the Panel suggests that a mechanism be instituted for direct funding of small and medium scale research equipment awarded under a responsive mode scenario. Such a grant programme has been used successfully in other countries to bring the laboratory infrastructure up to par with the best industrial and international standards.

3.6 THEORY

Several Panel members had the impression that UK university physics departments have fewer theorists than international comparison would lead one to expect. The Panel had no data with which to substantiate this anecdotal impression, but the Panel believed this observation to be sufficiently well founded for it to be worthy of a fuller, quantitative investigation by research policy specialists.

3.7 CENTRAL FACILITIES

The Central Laboratories (RAL and Daresbury) provide key infrastructure and essential facilities, often beyond the resources of individual universities, for implementing modern research in physics. They also provide a venue for interdisciplinary contacts and projects. The Panel felt that it could not make a thorough assessment without a more extensive study. Nevertheless, the Panel believes that under the constraints of present funding, these Laboratories are providing a valuable underpinning to significant components of UK physics research. They must continue to play an essential role in major future projects, both on and off-shore.

For the construction of large detector components for particle physics, the strong support group at RAL is a valuable asset. RAL and the ATC (in Edinburgh) also provide centralised astronomy support for space-based and ground-based instrumentation, respectively. These services are vitally necessary since UK university groups generally receive a lower level of support and suffer from poorer infrastructure in their institutions than groups from other, comparable European countries.

As already noted above, the Vulcan laser facility has become the most important facility world-wide for performing high intensity laser experiments. Outstanding work is also being performed at RAL on the neutron spallation source ISIS and, at Daresbury, in some of the sub-fields of physics which require synchrotron radiation. The Panel welcomes the decision to fund a new synchrotron radiation source and hopes that the needs of the UK soft x-ray/VUV community will not be neglected at the new facility. The Panel declines to comment on the siting issue.

The mode of access to central facilities (ticket system) is not optimal and the Panel welcomes the fact that this matter is now under review.

3.8 INTERNATIONAL FACILITIES

Many facilities needed for physics have been, and are being, organised on a European level (CERN, ILL, ESRF…). This trend will almost certainly continue and strengthen further. UK physicists are active members of most of these European ventures and their participation should be strongly encouraged. In addition to the national subscription, they require an adequate level of national support in order for them to use the facilities properly.

CERN is recognised as a world class laboratory for particle physics. The UK particle physics community is a major partner in the CERN facility. Their contribution through university groups and through RAL is highly appreciated intellectually and technically. Over the last few years, a significant share of the various scientific committee positions have been occupied by UK physicists, and senior positions in the coming LHC experiments are handled by university and RAL physicists.

The UK belongs to ESA and through it participates in large international solar and astronomical space observatories. However, it does not belong to ESO and the Panel felt that a strong case can be made for this now in order to have access to ESO's VLT and the international ALMA mm array. This move, although expensive, is probably necessary to arrest the decline in ground-based observational astronomy.

Likewise, UK physicists have played, and still play, key roles in the scientific programme and management of the ILL neutron source where there are important efforts in condensed matter and nuclear physics. The synchrotron radiation source ESRF is also a world-leading facility for structural biology, physics and materials science; although some experiments are highly visible, the Panel feels on balance that UK physics is under-represented.

3.9 RESEARCH ASSESSMENT EXERCISE

The Panel has decided not to comment on the mechanism of the quinquennial Research Assessment Exercise (RAE) which determines the allocation of funds to university departments by the Funding Council (one leg of the dual support system). A majority of the physics community now appears to appreciate the need for the RAE. The Panel concurs but points out that its application in a punitive way, i.e. giving little or no funds to poorly performing departments, does not provide the means for these departments to improve. Moreover, the situation is particularly difficult for isolated excellent research groups in poorly graded departments. The RAE apparently embodies a hitherto little used mechanism to 'flag' such groups. The Panel encourages its application.

The Panel heard repeatedly that while there may be little or no formal link between the RAE and the research funding policies of the Research Councils, in practice there is a real causal inter-relationship between the two sides of dual support. The RAE judges the strengths of previous Research Council investments while the peer review panels of the Research Councils are necessarily aware of the published RAE scores of the departments intending to host proposed research projects.

Not surprisingly, the Panel found a large dispersion in the quality of science between 5*, 5 and 4 RAE rated departments. Clearly, an elite level is being developed in a few top universities, with typically a perceptible step in quality between RAE 5 and RAE 4 departments. Some exceptions suggest that the rankings are not entirely frozen due to good management of resources.

The Panel concluded that a continuation of the present RAE-based funding system could eventually result in less than 20 research departments in physics which, indeed, seems to be in line with the ideas of the Secretary of State for Education in a recent speech. If this were to occur, the UK physics community would have to establish whether this number of departments would be sufficient to provide enough well-trained PhDs for the needs of the UK and to cover adequately all the important sub-fields in physics research. Moreover, the

Panel points out the mutual benefits of academic staff being involved in both teaching and research and thus the consequences for undergraduate teaching in universities outside the elite few.

3.10 RESEARCH COUNCIL FUNDING

The Panel concludes that a 'responsive mode' funding system naturally generates a mix of emphasis between physics sub-fields that is appropriate to national needs. Experience in other countries shows that measures taken to alter the resulting mix are usually not very successful. Such post-hoc adjustment necessarily faces the added difficulty of attempting to reshape an already established structure. The Panel believes that any moves to shape artificially the future direction of British physics research must be realistic in their ambition, and sensitive in their approach. The Panel therefore recommends that 'managed programmes' are used with restraint and that responsive mode funding is allowed to follow its natural course.

Catalysed by discussions with British colleagues – not only at the six universities visited – the Panel felt that EPSRC was not sufficiently aware of the need for continuity in the funding of certain projects. Nor were its peer review panels necessarily aware of the need to support or to recommend funding of projects which are highly innovative, perhaps with a lower than usual success expectation or which are even plain speculative! Interdisciplinary research and innovative proposals from young physicists, in particular, should receive more attention.

3.11 UK RESEARCH POLICY MECHANISMS

The Panel observed that UK research policy tends to favour overly rigid constraints on local decision making and tends to favour conservative and somewhat risk-averse science. In particular, it appeared to the Panel that the procedures governing post-graduate education and academic research careers in the UK are very rigid:

The Panel was puzzled that all graduate students in physics are expected to finish the PhD degree in three years. This period is shorter than in scientifically competitive countries, and as a result, British PhDs are generally less able to move in new directions, and are less experienced and well-trained than their peers from abroad. This is particularly true if the PhD follows directly on from a three-year BSc.

The Panel also noted that there are no regular provisions for permanent (long-term) research positions attached to university research groups. The lack of such positions causes some research scientists to lead careers of serial post-doctoral appointments, a situation that is unacceptable.

There is little scope in the UK for individual institutions to make local rules and advance local priorities. The Panel asks why, for example, post-doctoral salaries are fixed by a formula that essentially ignores experience and the market forces that determine salary scales among the different professions outside the university sector.

The Panel noted that the flow and mobility of students is largely determined by national funding policies. As a result, in some ways the UK universities appear to regard students fundamentally as a source of income. For instance, students are effectively barred from enrolling in the fourth year of the MPhys/MSci course at institutions other than that in which they initially enrolled. A free-standing fourth year at a different institution could provide an excellent opportunity for students to broaden themselves. This would permit a wider choice of research project and could stimulate healthy competition between the universities.

APPENDIX A

DATA SUPPORTING THE REVIEW

A.1 MAIN DATA DOCUMENT

All members of the International Panel were provided with a 60 page document compiled at the Institute of Physics specially for the Review. The document contained the following entries:

Introduction
Comprehensive Spending Review
Science budget
Research income, UK university departments by discipline
Cost of international facilities
Research Assessment Exercise (1996), results UoA 19
Research Assessment Exercise (2001), criteria and methods
Funding Council research allocation to university departments
Income to departments (excluding Funding Council allocation)
International comparative data for university physics personnel
Age profile of the UK academic community
Results of the Institute of Physics salary survey 1998
Profile of physics community by sub-field
PhD Studentships – time trends by sub-field
Research Fellowships, numbers by sponsor 1998/99
Employment destinations of PhDs and Post-docs
First degree and PhD outputs
PPARC performance indicators
Bibliometrics
List of acronyms

A.2 DATA LIBRARY

In preparation for the visit of the International Panel, the Institute of Physics assembled and catalogued a library of documents and statistics to assist the Panel with its enquiries. The library comprised books, reports and electronic data. During the week of the Review the Secretariat obtained information for the Panel on the following topics from the Data Library and from other sources:

- Four year undergraduate degrees in physics (MPhys/MSci)

- Salaries of post-doctoral researchers

- Academic appointments and faculty mobility

- Participation in international conferences
- Numbers studying physics in the UK at A-level
- Age distribution of those securing long-term faculty posts
- Data on initiatives to support university research infrastructure
- Information on research technicians
- Women in physics

In addition the Panel raised several questions concerning bibliometric assessments of research impact.

A. 3 BIBLIOMETRICS

Three sets of bibliometric information were made available to the Panel.

The first formed part of the Main Data document. This consisted of an introduction to bibliometrics; a report of an expert assessment of the benefits and problems of bibliometrics and reports on six recent bibliometric studies concerning physics in the UK. Most of these studies report assessments of the relative citation impact (RCI) for physics in the UK.

The UK relative citation impact for physics is defined by the expression:

[(Citations to UK physics)/(UK Physics papers)]/[(Citations to World physics)/(World Physics papers)]

The review of existing bibliometric literature was prepared by the support group to the International Review and drew upon the materials listed below.

- *Bibliometric indicators and analysis of research systems: models and examples*, Yoshiko Okubo, OECD STI Working Paper 1997/1.
- *Benchmarking of the international standing of research in England*, Centre for Policy Studies in Education, University of Leeds, November 1997.
- *The scientific wealth of nations*, Robert M. May, Science, 7 February 1997, p. 793.
- Engineering and Physical Sciences Research Council, In-house bibliometric analysis 1999.

- Particle Physics and Astronomy Research Council, Bibliometric analysis of astronomy, A.D. le Masurier, 1999.
- Institute for Scientific Information, *Science in the United Kingdom* 1994-1998 and *Science in Canada* 1994-1998. www.isinet.com, 2000.
- *Scale independent indicators and research evaluation*, J. Sylvan Katz, Science and Public Policy, to be published.

The original studies referred to in the Main Data Document relied in most cases, on the raw data sets available from the Institute for Scientific Information (ISI) based in Philadelphia, USA.

In particular the Panel noted the Relative Citation Impact (RCI) results obtained by the various bibliometric researchers. The Panel noted that the reported RCIs for UK physics vary between different reports as a result of methodological differences or differences of definition.

The Panel notes that:

Invariably the US leads the list of G7 countries in conventional RCI measurements.

UK physics is reported as having an RCI in the range 1.09 – 1.33, when defined conventionally.

The RCI results for UK physics are very similar to those obtained for comparable countries such as Germany and France.

The second bibliometric data set to which the Panel had access was a compilation of the results of the *Hot Papers* listings of ISI's Science Watch covering citations over a ten-month period from March 1999. These listings led to a master list of approximately 110 highly cited papers in physics. The criterion to appear in the master list is that a paper has received at least five citations in any of the five bimonthly periods considered. The papers were assigned to the relevant sub-field of physics by support staff to the Review and papers were related to key countries of interest on the basis that any author has an address from that country. The overwhelming majority of the papers have at least one US author, while UK authors were significantly less well represented (but to the same extent as Germany and France).

The third set of bibliometric data was provided by the Institute of Physics and is a comprehensive database from ISI entitled *High Impact Papers*. It contains the most influential papers in specific fields in the sciences and social sciences, as reflected by citations tabulated from 1981 to 1995. Each sub-field contains complete bibliographic information on its 200 most-cited papers drawn from an annual total for all sub-fields of 3,400 papers. Data include all author names, all author addresses, journal title, and year-by-year and total citation counts for each paper. The sub-fields that clearly belong to 'physics' are applied physics, atomic physics, condensed matter, fluids and plasmas, (general) physics, instrumentation, mathematical physics, nuclear physics, optics and particle physics.

As expected, the US plays a dominant role with 2000 – 3000 papers in each sub-field in the fifteen-year period. France, Germany, Japan and the UK (and in one or two cases Italy and Canada) form a second group with 200 – 800 papers in each sub-field. The UK leads this group in fluids and plasmas, materials physics and optics, but trails it in applied physics and condensed matter physics.

A. 4 SITE VISITS

In order to provide contextual information to support the Review, the Panel visited seven sites in the UK. The panel split into three sub-groups each of which visited two universities. The universities were selected to illustrate substantial research departments (RAE grades 4, 5 and 5*) and to illustrate the regional diversity of physics research departments. The seventh site was the Rutherford Appleton Laboratory of the Central Laboratory of the Research Councils. This was visited by the entire Panel.

To support the site visits the Panel members were provided with information packs prepared by the sites to be visited in collaboration with the Review support team. These packs provided data on the site and its physics research as well as providing an insight into the research priorities.

A.5 PRIMARY LITERATURE

At the suggestion of the Advisory Group the study support group prepared bound volumes of representative recent physics research papers, as selected by heads of department at nine universities in the UK. The set of nine universities included the six visited by the sub-groups of the Panel. The nine bound volumes provided a substantial body of recent pre-selected primary literature for consideration by the Panel.

APPENDIX B

QUESTIONNAIRE WITH ACCOMPANYING LETTER (EMAIL)

Dear . . . . ,

At present, an International Panel, of which I am a member, is evaluating physics in the UK at the request of the Institute of Physics, the Royal Astronomical Society and the two responsible Research Councils, EPSRC and PPARC. According to the terms of reference, the Panel will report on the standing, balance and potential of physics research in the UK, and provide a comparison with physics research internationally. Our major problem is that we are only able to visit six representative university physics departments as well as Rutherford Appleton Laboratory. Moreover, our own expertise does not cover the whole of physics. To help in this situation each Panel member is sending the questionnaire below to about 10-15 colleagues in his own and related fields. We would be very grateful if you could help us by filling out the questionnaire and returning it to me within the next few days.

This exercise does not pretend to be an exhaustive survey. The questions are intended to assess your general impression of UK physics and do not represent a formal or rigorous evaluation of precise research disciplines. Please complete questions 1 and 2, and as many of the rest as you feel you can answer. All responses will be treated confidentially; only aggregated results will be used.

Thanks for your time!

Best wishes,

ALEXANDER M. BRADSHAW
Chairman of the International Review Panel

QUESTIONNAIRE

1. What is your own field of expertise (in a few words)?

2. How would you rate your degree of awareness of UK research in your broad field of expertise?

a. high
b. low
c. unaware

3. Considering only the best two or three research groups in the UK in your broad field of expertise, do you consider that their research quality in international comparison (US, Western Europe, Japan) is

a. leading
b. higher than average
c. about average
d. lower than average

(You may wish to mention which groups these are, but it is not necessary)

4. Do you consider that, taken overall, UK research in your field is internationally

a. leading
b. higher than average
c. about average
d. lower than average

5. In your broad field of expertise, do you consider that the ranking of UK research in an international context, when compared with the situation 10-20 years ago, is:

a. much better
b. better
c. about the same
d. worse
e. much worse?

6. If you think of the three most exciting developments in your broad field of expertise in the last 5-10 years (you may name them if you wish), have UK physicists been involved

a. at the forefront in an innovative way
b. in a more derivative way, somewhat behind the leaders
c. hardly at all?

(If **a**. applies, are there also examples where results reported by UK groups have broken entirely new ground and other groups have then followed?)

7. Do you have any further comments?

APPENDIX C

ACRONYMS

ALMA	Atacama Large Millimetre Array
ATC	Astronomy Technology Centre, Edinburgh
CCLRC	Council for the Central Laboratory of the Research Councils (CLRC)
CERN	Conseil European pour la Recherche Nucleaire
CMS	Compact Muon Solenoid
CRESST	Cryogenic Rare Event Search with Superconducting Thermometers
CSAR	Computer Services for Academic Research
DESY	Deutsches Elektronen-Synchrotron
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESO	European Southern Observatory
ESRF	European Synchrotron Radiation Facility
FIRST	Far Infrared Space Telescope
FNAL	Fermilab
GANIL	Grand Accelerateur National d'Ions Lourds
GPS	Global Positioning System
ILL	Institut Laue-Langevin
ISOL	Isotope Separator On Line
ISI	Institute for Scientific Information
JCMT	James Clerk Maxwell Telescope
JET	Joint European Torus
JIF	Joint Infrastructure Fund
JREI	Joint Research Equipment Initiative
LEP	Large Electron Positron Collider
LHC	Large Hadron Collider
LISA	Laser Interferometer Space Antenna
MPhys/MSci	Four year undergraduate degree in physics
MERLIN	Multi-Element Radio-Link Interferometer
MRI	Magnetic Resonance Imaging
OST	Office of Science and Technology
PPARC	Particle Physics and Astronomy Research Council
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
RAE	Research Assessment Exercise
RAL	Rutherford Appleton Laboratory

RAS . . . . Royal Astronomical Society
RIA . . . . Rare Isotope Accelerator
SLAC . . . . Stanford Linear Accelerator
SNO . . . . Sudbury Neutrino Observatory
TRIUMF . . . . Tri-Universities Meson Facility
UKAEA . . . . United Kingdom Atomic Energy Authority
VISTA . . . . Visible and Infrared Survey Telescope for Astronomy
VLT . . . . Very Large Telescope

THE INSTITUTE OF PHYSICS is an international learned society and professional body. Its membership, of over 30,000, continues to grow steadily. It looks after the interests of professional physicists and supports the education of the physicists of tomorrow. The Institute promotes knowledge in physics through conferences, activities to raise public awareness and understanding of physics and publishing through Institute of Physics Publishing, a major publisher of physics both on paper and electronically.

THE ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL is the largest of the United Kingdom's seven government-funded research councils. Its mission is to support the highest quality research and related postgraduate training in engineering and the physical sciences. EPSRC aims to advance knowledge and technology and provide trained engineers and scientists for the benefit of the United Kingdom and the quality of life of its citizens. It has the further role of promoting public understanding in engineering and the physical sciences.

THE PARTICLE PHYSICS AND ASTRONOMY RESEARCH COUNCIL (PPARC) has a mission to pursue a programme of high quality basic research in astronomy, planetary science and particle physics which furthers our understanding of fundamental questions, trains high quality scientists and engineers, increases UK industry's competitiveness, attracts future generations of scientists and engineers, and stimulates the public's interest.

THE ROYAL ASTRONOMICAL SOCIETY was founded in the year 1820 and received the grant of a Royal Charter in 1831. The Society's aims are "the encouragement and promotion of astronomy and geophysics". The main functions are to publish the results of astronomical and geophysical research, to maintain as complete a library as possible in these subjects and to hold meetings, in London and elsewhere, at which astronomical and geophysical matters can be discussed.

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