
The Physics of Nuclei, Nuclear Matter and Nucleosynthesis

Report of the Nuclear Physics Advisory Panel

31 October 2012

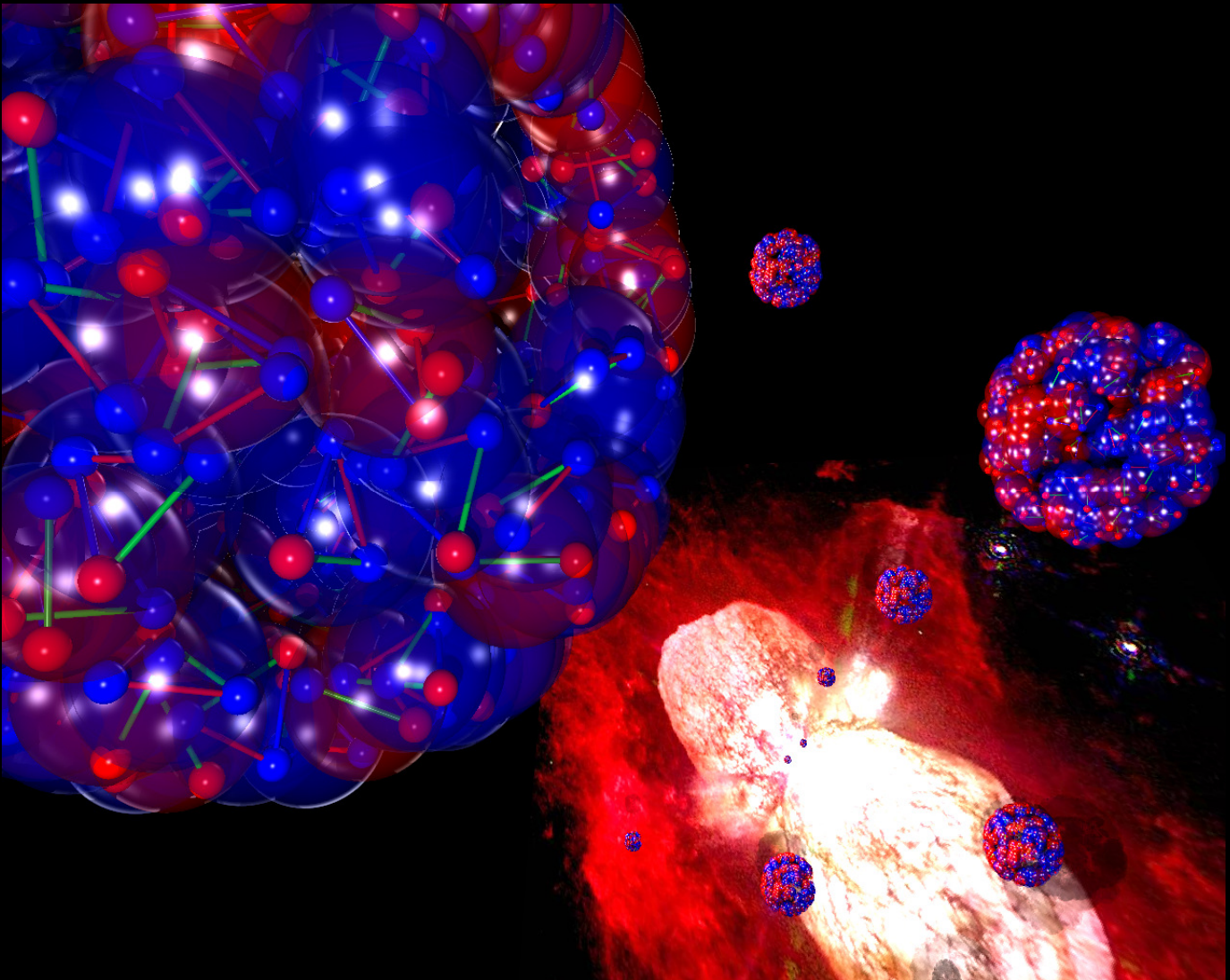


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1 Summary

The next ten years in nuclear science will see the great advances in our insight into strongly interacting matter. These include the nature of matter an instant after the Big Bang (the Quark Gluon Plasma - QGP), the nature of the strong force within hadrons through the characterisation of mesons and baryons, determination of the quark and gluonic structure of nucleons, the study of key reactions associated with the driving of spectacular novae, supernovae and X-ray bursters, through to the determination of the structure of nuclear matter at the extremes of stability and angular momentum thus driving the development of the understanding of the strong interaction on the nuclear scale and the synthesis of new atomic elements. The UK has developed scientific leadership in all of these areas.

The UK currently has one Nuclear Physics project, NuSTAR. This is developing equipment for the experimental programme at FAIR, GSI, Germany. FAIR will be the premier international fragmentation facility in the world and will produce high intensity beams of exotic nuclei which will allow the UK to take advantage of leadership in the area of nuclear structure and nuclear astrophysics to study the most neutron-rich nuclei yet produced, test our understanding of the strong interaction at the extremes, how elements are synthesised in supernovae, through the r-process, and the structure of matter inside neutron stars. This complements on-going exploitation programmes at international facilities – where UK groups obtain beam time in a competitive process based on scientific merit.

Building on the established strengths in scientific leadership and strong track record in developing innovative detection systems and state-of-the-art instrumentation, the UK has developed 5 projects which will enhance this leadership. Correspondingly, the community has submitted 5 Statements of Interest (SoIs) to Science Board which represent the opportunity for high impact science across the breadth of the programme.

The current lack of breadth in projects in the nuclear physics programme, places the UK in a fragile position. The STFC 2011-12 Operating Plan observed: “The lack of a development line for future [nuclear physics] projects could cause long-term damage to the NP programme”. The loss of leadership in the PANDA experiment at FAIR and the diminishing role in AGATA is an example of this damage. It is imperative that STFC funds a series of nuclear physics projects to underpin existing world-leading capabilities. The community believes that these need to be spread across the key programmatic areas of “nuclear structure and nuclear astrophysics” and “hadronic physics”. As such funding scenarios are examined in this report in these categories.

Recommendations:

- **The UK Nuclear Physics Community requires a balanced programme of projects across the areas of *Hadronic Physics* and *Nuclear Structure and Astrophysics*.**
- **Rather than prioritising between projects it is possible to accommodate a range of projects through profiling project spend – as illustrated in this report.**
- **An uplift in the number of nuclear physics projects and funding is required.**
- **STFC should seek to promote nuclear theory, through continuing existing support and co-funding a new University Chair in Nuclear Theory.**

2 Science Questions

Nuclear Physics is answering questions which define our understanding of systems from the largest (astronomical) to the smallest (hadronic) scale. These were set out in the previous report of the Nuclear Physics Advisory Panel¹ (the present and future programmes reflect these scientific goals).

What are the Origins of the Elements?

- How, and where, were the heavy elements synthesised?
- What are the key reaction processes that drive explosive astrophysical events such as supernovae, and X-ray bursts?
- What is the equation-of-state of compact matter in neutron stars?
- What are the nuclear processes, and main astrophysical sites, that produce the γ -ray emitting radionuclides observed in our galaxy?
- How do nuclear reactions influence the evolution of massive stars, and how do they contribute to observed elemental abundances?

What is the Nature of Nuclear Matter?

- What are the limits of nuclear existence?
- How do simple patterns emerge in complex nuclei?
- Can nuclei be described in terms of our understanding of the underlying fundamental interactions?
- What is the *equation-of-state* of nuclear matter?
- How does the ordering of quantum states change in extremely unstable nuclei?
- Are there new forms of structure and symmetry at the limits of nuclear existence?

How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?

- What is the mechanism for confining quarks and gluons in strongly interacting particles (hadrons)?
- What is the structure of the proton and neutron and how do hadrons get their mass and spin?
- Can we understand the excitation spectra of hadrons from the quark-quark interaction?
- Do exotic hadrons (multi-quark states, hybrid mesons and glueballs) exist?
- What are the phases of strongly interacting matter and what is the nature of the quark-gluon plasma?
- How do nuclear forces arise from QCD?

The first two themes are associated with “nuclear structure and nuclear astrophysics” and the third “hadronic physics”.

¹ http://www.np.ph.bham.ac.uk/community/npap/report_nov09.pdf

3 The Current UK Nuclear Physics Programme

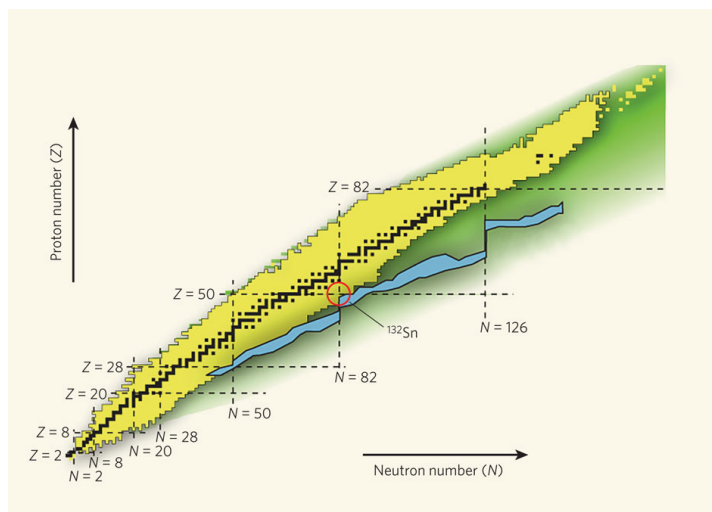
NuSTAR, as funded, left the UK involved in 3 experiments associated with FAIR at GSI i) R3B, ii) DESPEC and iii) HISPEC. The UK's contribution to the R3B project involves the construction of the recoil detector which will be used for quasi-free knockout measurements which are led by the UK. Such studies provide a key insight into the structure of nuclei close to the limits of stability and are one of the ultimate tests of state-of-the-art nuclear theory at this limit. The UK part of the

DESPEC collaboration is developing a new Lanthanum Bromide gamma-ray array capable of detecting gamma-ray coincidences with a time resolution permitting the characterisation of key nuclear states in exotic neutron-rich nuclei. The physics to be probed is the structure of nuclei relevant to the r-process (rapid neutron capture process by which many of the heavier elements are formed in supernovae). HISPEC is a project to use high energy beams of very exotic (neutron-rich) nuclei in conjunction with the AGATA array to measure electromagnetic transitions in hitherto unstudied nuclei – a key test of their structure. The UK's investment in these projects has placed the community in a strong position in which the potential for scientific impact is significant. This has been vital for sustaining scientific and technical leadership for the UK community.

As such, **continued funding for the currently funded NuSTAR is a priority.**

The UK is currently pursuing Associate Membership to FAIR, which would permit the UK to sit on the FAIR board and access to the decision making process linked with FAIR.

In addition to the construction of the equipment at GSI, the NuSTAR collaboration has involvement with the AGATA project – which is an important element of HISPEC. AGATA is a state-of-the-art, multi



The chart of nuclei. Black are stable elements, yellow are unstable, beta-decaying that have been studied to-date and green nuclei that remain to be produced in the laboratory. The blue region indicates the path of the r-process in supernovae. The limits of stability (edge of green region) are only known for the lightest systems. From http://www.nature.com/nature/journal/v465/n7297/fig_tab/465430a_F1.html



The new FAIR facility in Germany

element, germanium detector array with the ability to track gamma-rays as they interact within the detectors. This ability to localise the interaction point, and hence the angle of incidence of the gamma-ray, presents a number of experimental advantages in terms of enhancing resolution and sensitivity which are being used to unlock new areas of physics.

FAIR is currently being constructed and will not start operation until 2018. From the period of 2014 until 2018 there will be no experimental programme.

In addition to the NuSTAR project the UK has active experimental programmes funded through the consolidated grants line, utilizing equipment funded through earlier EPSRC/STFC grants² (see appendix . Exploitation is currently the largest component of the research programme. Access to these facilities has historically been free to the user and based on scientific merit, with the expectation that the quid-pro-quo is the construction of experimental infrastructure which is made available to other facility users. Given the UK has no domestic facility, the community has worked almost exclusively in this mode for the last 20 years.

Prior to the last programmatic review, the UK was involved in three projects; PANDA, AGATA and NuSTAR. The removal of project funding for all but NuSTAR resulted in significant reduction in international leadership, reputation and scientific opportunity. This leadership in electronics, instrumentation and detector development (of all types of radiation; gamma, charged particle, neutron,...) together with mechanical design is associated with only a few key projects. It is now widely recognised that a single project is not sufficient to create adequate scientific opportunity for the entire community. **There is a significant risk that if there is not further diversification in the near future that the community will unsustainably shrink and scientific leadership will be irrevocably lost.**

Beyond the UK, the body that represents nuclear physics in Europe, NuPECC has set its priorities for nuclear structure and astrophysics which include (a) Complete facilities (FAIR, SPIRAL2 at GANIL), (b) Perform major upgrades (e.g. HIE-ISOLDE, AGATA) and (c) Work to get EURISOL on the ESFRI list.

² Current exploitation facilities: ALICE, CERN; Argonne National Laboratory, US; DESY, Germany; Florida State University, US; GANIL, France; GSI, Germany; ILL, Grenoble, France; ISOLDE, CERN; iThemba Labs, South Africa; JAEA (Japan Atomic Energy Agency), Tokai, Japan; Australian National University (ANU); Jefferson Laboratory, US; Jyväskylä, JYFL, Finland; Legnaro, Italy ; Mainz, Germany; Max Lab., Lund, Sweden; Michigan State University, MSU, USA; Munich, Germany; Orsay, France; RIBF RIKEN, Japan; Texas A&M, US; TRIUMF, Canada; Bucharest; Notre Dame, US; RCNP Osaka, Japan.

4 Future Opportunities:

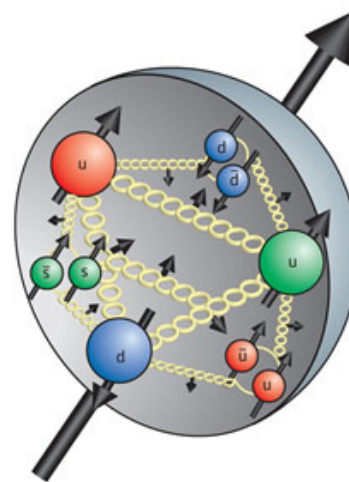
The future developments of the subject have been broken down into two areas; *hadronic physics* and *nuclear structure and nuclear astrophysics* below³.

4.1 Hadronic Physics.

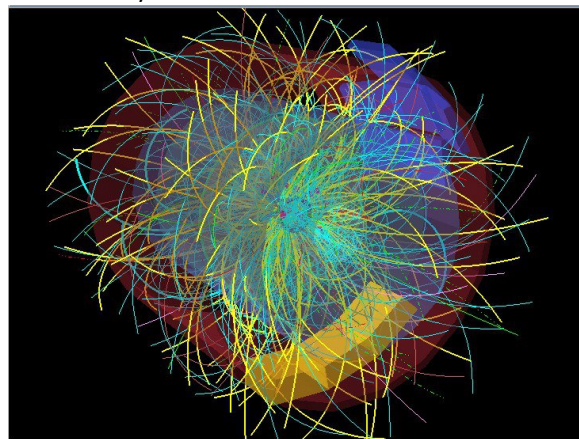
Whilst most textbooks would suggest a simple system composed of 3 spin 1/2 quarks, experimentally this is found to be far from the truth – only 30% of the proton spin arises from the spin of the quarks. The remainder is a ferment of gluons and virtual particles, which conspire together with the quark orbital motion to give a spin of 1/2 – precisely how remains a mystery. New experiments with improved sensitivity are being developed to answer such questions. This challenge of describing nucleons within the framework of Quantum Chromodynamics (QCD) complements that of understanding the nucleus from the interaction of the constituent nucleons. It should be noted that it is often overlooked that 99% of mass can be attributed to the strong interaction and not the Higgs mechanism. An understanding of the structure of the proton may be achieved through measurements of generalised parton distributions (GPDs) which allow a three-dimensional image of the proton to be reconstructed, thus permitting the contribution to the spin of the orbital angular momenta of the constituents to be determined. Understanding the nature of the strong interaction from a QCD perspective is also strongly informed by the properties of quark-antiquark systems (mesons). By exciting the quark-antiquark pair, producing resonances, it is possible to gain an insight into the nature of gluonic exchange binding the system. There is the potential for the discovery of excitations of the gluonic *string* between the quarks.

The most extreme test of nuclear matter occurs when nuclei collide at energies at which the energy density reaches $0.7 \text{ GeV}/\text{fm}^3$ (5 times normal nuclear matter density). At such densities the nucleons dissolve into their quark constituents, undergoing a phase transition.

The structure of the proton (credit RIKEN).



Event reconstruction from the ALICE experiment for a heavy-ion collision



³ It is important to note that the number of academics associated with each project is not exclusive as several have interests in a number of different projects. Further, it is unlikely that in funding a particular project that all those associated with the project will benefit directly – many academics operate in “exploitation only” mode. Benefit may be indirect through the subsequent exploitation programme.

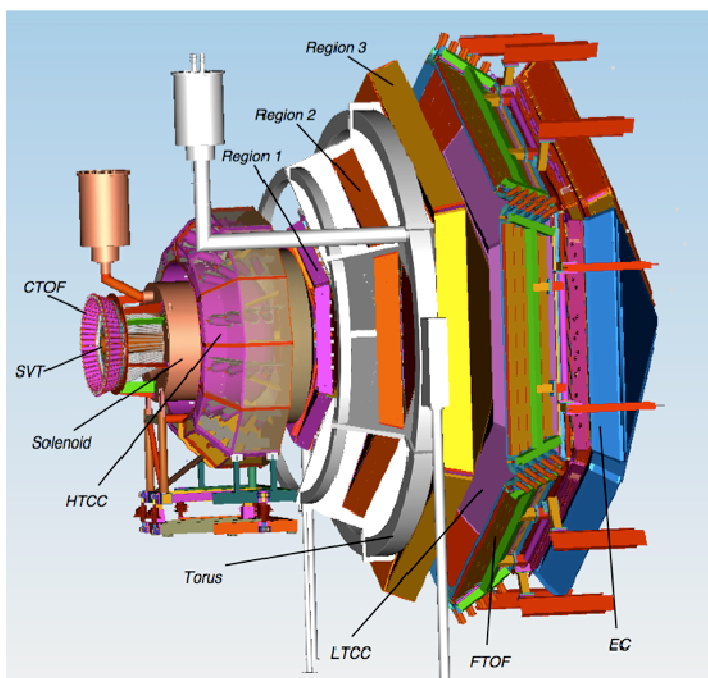
This provides a laboratory test of the nature of matter a short instant after the Big Bang. A description of such a phase of strongly-interacting matter within QCD remains a challenge, as does its experimental characterisation.

4.1.1 Future Projects

4.1.1.1 JLAB-upgrade:

JLab had until recently a 6 GeV electron accelerator for studying electron and photon interactions with nucleons and nuclei. These provide an insight into the structure of the nucleon, e.g. through measurements of the proton and neutron electric and magnetic form factors – which give an insight into the behaviour of the constituent quarks. The accelerator is currently undergoing an upgrade to 12 GeV, and an associated upgrade to the experimental equipment.

The scientific vision behind the upgrade to the Thomas Jefferson National Accelerator Facility (JLab) is to reveal how Quantum Chromodynamics (QCD) works in nucleons and nuclei; addressing fundamental questions such as how constituent quarks acquire mass, and why they are confined. This project will enable UK groups to make a significant impact in the science programme at the upgraded lab, capitalising on current leadership roles in the future programme, and exploiting the synergies of leading research in two collaborations – CLAS (to be upgraded to CLAS12) and Hall A – to develop three detector subsystems: a Forward Tagger and a Ring-Imaging Cherenkov (RICH) detector for CLAS12, and the Super Bigbite Spectrometer (SBS) in Hall-A. This contribution to the world’s leading hadron physics facility will permit continued leadership of science in the areas of hadron spectroscopy and nucleon structure.



A schematic of the CLAS12 detector, an upgrade of the existing Hall B CLAS detector to match the 12 GeV electron beam.

Science Reach: *How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?* What is the mechanism for confining quarks and gluons in strongly interacting particles (hadrons)? What is the structure of the proton and neutron and how do hadrons get their mass and spin? Can we understand the excitation spectra of hadrons from the quark-quark interaction? Do exotic hadrons (multi-quark states, hybrid mesons and glueballs) exist? How do nuclear forces arise from QCD?

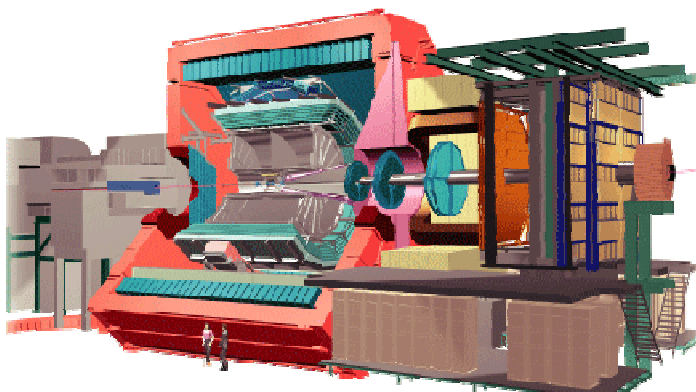
Scientific leadership: Leadership roles in CLAS12, experiments approved with CLAS12. Chair of CLAS hadron physics working group, member of CLAS Coordinating Committee. Approved experiments with CLAS12 and Hall A. Leadership roles in EU FP7 I3 *Hadronphysics3*.

Technological Expertise/Drivers/Impact: Experts in RICH detectors, photon tagging, production of polarised beams using diamond radiators. Role in upgrade of Bigbite spectrometer. Key technologies: GEM chambers, inorganic scintillators, fast photon detection systems, polarimeters and electronic readout systems.

Institutions: 2. Academics: 6

4.1.1.2 ALICE-upgrade

A precise determination of the QGP properties would be a major scientific achievement and go a long way towards a better understanding of QCD as a genuine multi-particle theory. The ALICE experiment plans upgrades which encompass a number of detector, trigger, software and computing developments that will be required to continue the exploitation of



Schematic of the ALICE detector at the LHC.

ALICE throughout and beyond the next decade. Upgrades are required to cope with the anticipated increase in the Pb beam luminosity to $L = 6 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$, which will deliver Pb-Pb interactions at 50 kHz. The UK is proposing to play a major role in the upgrade of the Inner Tracking System (ITS) in three areas where it has recognised international leadership. These are the pixel sensor development, the stave and barrel design, construction and assembly and the trigger development. In particular, they will capitalise on the world-leading expertise the UK has in the development of Monolithic Active Pixel Sensors (MAPS). The main motivation for the upgrade is to achieve a precise, quantitative, understanding of the properties of the de-confined QGP by focusing on rare probes both at low and high transverse momenta as well as on multi-dimensional analysis of such probes with respect to centrality, event plane, multi-particle correlations, etc. This programme requires high precision measurements and statistics. This project will build on the prior investment of STFC in the ALICE experiment by sustaining and enhancing the leadership role the UK plays in ALICE and hence this area of science.

Science Reach: **How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?** What is the physics of the early universe? What is the nature of nuclear and hadronic matter? How do the laws of physics work when driven to the extremes?

Scientific Leadership: Built and commissioned ALICE trigger – provide key support for the trigger during experiments. Membership of ALICE Management and Collaboration Boards. Membership of the ITS Upgrade Steering Committee. Links to UK group at RAL who are world leaders in MAPS technology.

Technological Expertise/Drivers/Impact: Proposal is to develop a large scale silicon detector using MAPS technology and develop a new trigger system for ALICE. Experts in sophisticated trigger design and development. Experience with MAPS technologies. Developed large silicon arrays – in collaboration, e.g. ATLAS and LHCb. Key development is MAPS detectors – potentially create UK leadership.

Institutions: 3. Academics: 4

4.1.2 Funding Consequences:

Lack of funding for the hadronic physics projects could see over the next 5 years a decline in a research area which the UK has fought hard to secure scientific leadership and has tremendous potential for scientific return; nature of the quark-gluon-plasma and the structure of the nucleon. These are two areas which have been developed through continued investment over a period of over 20-30 years. Maintaining leadership will only be through the ability to drive the technical development of these areas.

4.1.3 Longer Term Directions in Hadron Physics

The longer term future (2020+; horizon) in hadronic physics will be to focus on the gluon content of matter, since this is at the centre of why strongly interacting matter is the way it is. This will be realised by the construction of an electron-ion collider (EIC). Rather than using complex nucleon-nucleus or nucleus-nucleus collisions this will use the electron as a probe of the gluons inside the nucleus. The well characterised interaction would permit for example, precision imaging of the sea-quarks and gluons to determine the spin, flavour and spatial structure of the nucleon and a definitive study of the nature of strong gluon fields in nuclei – providing a simultaneous understanding of the strong interaction within the nucleon and nucleus.

There are several proposals to build electron-ion colliders. One possibility would be based at FAIR as an extension to PANDA. Alternatively, at JLab a current proposal involves an electron-ion collider (ELIC) with centre-of-mass energy of 20 to 65 GeV and a luminosity up to $8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with polarised beams of p, d, ^3He and Li, and unpolarised light to medium ion species (e.g. up to ^{40}Ca). This would form a natural longer term development of the present hadron physics programme. Other possible options are electron-ion-collider experiments being considered at Brookhaven (ERIC) and the LHC (LHeC).

The previously described ALICE-upgrade will provide access to a greater range of probes of the quark-gluon plasma, and the 12 GeV upgrade at JLab will study the structure of the nucleon and the nature of the strong interaction via the study of resonances in hadrons. There is an exciting prospect that both these strands of research will come together in the physics programme of the EIC. The two communities will be able to combine their expertise to form a strong UK contribution. It is crucial to build a reputation in the interested community now to take future leadership in the formation of the physics programme, detector development and science exploitation of future EIC experiments.

4.2 Nuclear Structure and Nuclear Astrophysics.

The scientific objectives associated with nuclear structure are captured by the two questions: *What are the Origins of the Elements?* and *What is the Nature of Nuclear Matter?* Some broader context is given in appendices 10.1 and 10.2.

Major goals include: characterisation of nuclear matter at and beyond the limits of nuclear stability (e.g. when neutrons or protons will no longer stick to the nucleus); characterisation of the strong *nuclear* force beyond the stable nuclei; developing accurate first principles models of nuclei which can be applied across the full spectrum of nuclei – light to heavy, stable to radioactive, bound to unbound; determination of key reaction paths associated with energy generation and element synthesis in quiescent burning, novae, supernovae and X-ray bursts; determination of the nature of matter in neutron stars; the synthesis of new superheavy elements.

There are two main types of experimental facility being developed worldwide which the UK plan to exploit: Fragmentation radioactive beams (e.g. FAIR/NuSTAR) and ISOL type radioactive beams (e.g. ISOLDE/HIE-ISOLDE). Proposed UK projects are associated with the development of equipment for these facilities.

The great advantage of the relativistic beams of FAIR is their reach in terms of neutron to proton ratio (isospin) – there is the potential for the study of the most extreme isospin nuclei yet produced. This allows the strong interaction at the point where nuclear matter becomes unbound to be tested and properties of r-process nuclei to be evaluated.

However, the quality of the beam which is produced in such a fragmentation facility limits precision measurements of nuclear reactions which have been used to reveal important detail of nuclear structure as it evolves towards the extremes of isospin. Moreover, the energies are completely mismatched for the study of nuclear reactions at the energies at which they occur in stellar processes. For these reasons it has been widely recognised that two types of facility are required; high energy fragmentation (e.g. NuSTAR) and ISOL (e.g. ISOLDE, CERN and/or SPIRAL 2, France). Within Europe there is the expectation that the world-leading EURISOL (ISOL) facility will be constructed on a timescale of 2020+. On the path to the construction of EURISOL there are major construction/upgrade programmes to build next generation ISOL facilities – these include HIE-ISOLDE at CERN and SPIRAL2 at GANIL, France. The UK has an established low-energy programme and scientific pedigree through existing programmes at ISOLDE, GANIL and other ISOL facilities such as TRIUMF in Canada. As such there is a very strong imperative for the development of new pieces of experimental equipment for HIE-ISOLDE and/or SPIRAL2 in addition to FAIR/NuSTAR. It should also be noted that the UK makes a subscription to ISOLDE through the CERN subscription.

4.2.1 Future Projects

4.2.1.1 NuSTAR2

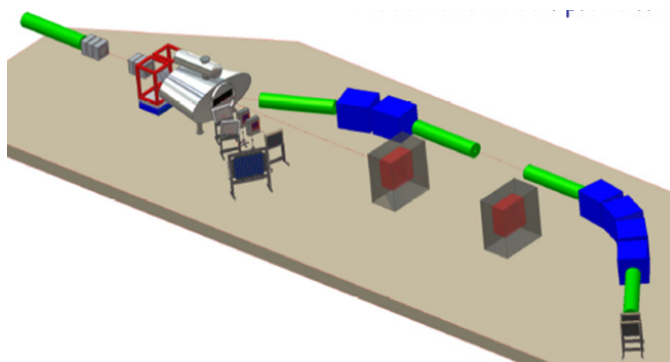
NuSTAR at FAIR (Facility for Antiproton and Ion Research) will be *the* leading **fragmentation facility** in the world - providing beams of exotic nuclei from protons to uranium, independent of their chemical properties. The facility will be unique in many respects: (i) experiments can be carried out at high energies per nucleon up to 2 GeV and (ii) it will provide fragmentation beams for heavy nuclei.

NuSTAR2 will extend the science reach of existing equipment associated with the R3B and DESPEC projects and develop new strands which play to the strengths of the current UK community, currently untapped at FAIR. In the case of the latter, the most fundamental properties of nuclei include their ground-state spin, radius and magnetic and electric moments. These are vital for constraining state-of-the-art nuclear theory. Measurements of these properties can be achieved using the hyperfine interaction as a probe. The UK is a world-leader in this field and the extension of the existing programme to the most exotic nuclei would be a major development.

New opportunities include: single ion mass and lifetime measurement, laser spectroscopy, study of nucleon wave-functions for the most neutron-rich nuclei, and high resolution gamma-ray spectroscopy for decay studies. It will give the UK access to the ILIMA (Isomeric states, Lifetimes and Masses) and LaSpec (Laser Spectroscopy) collaborations in which the UK has scientific leadership, and it will allow the UK to

maintain leadership roles in R3B (Reactions with Relativistic Radioactive Beams) and DESPEC (Decay Spectroscopy).

These developments will permit the science programme to extend the characterisation of nuclei important for the rp- and r-processes and push deeper towards the neutron and proton drip-lines for heavier nuclei, thereby permitting nuclear models to be tested at the extremes of neutron to proton ratio. They will also provide opportunities for the enhanced characterisation of the equation-of-state of neutron matter – key for the modelling of neutron stars. It is this facility which will have the greatest reach in terms of accessing new nuclei and correspondingly has great discovery potential.



The proposed modification to the R3B setup which would include a high momentum magnetic spectrometer (blue and green). The UK also proposes to build a TPC-like active target. Both developments increase the scientific reach and international competitiveness.

Science Reach: What are the Origins of the

Elements? What are the key reaction processes that drive explosive astrophysical events such as supernovae, and X-ray bursts? What is the equation-of-state of compact matter in neutron stars? ***What is the Nature of Nuclear Matter?*** What are the limits of nuclear existence? How do simple patterns emerge in complex nuclei? Can nuclei be described in terms of our understanding of the underlying fundamental interactions? What is the equation-of-state of nuclear matter? How does the ordering of quantum states change in extremely unstable nuclei? Are there new forms of structure and symmetry at the limits of nuclear existence?

Scientific Leadership: UK has spokespersons for the DESPEC and ILIMA collaborations, Technical Director for R3B project, representation on the NuSTAR board. Long track record of obtaining beam time. Currently building key components of the DESPEC, HISPEC and R3B projects and have scientific leadership in key areas (e.g. decay/gamma-ray spectroscopy and quasi-free knock-out reactions). UK has world-renowned leadership in the fields of laser spectroscopy and study of nuclear isomers (long lived nuclear states).

Technological Expertise/Drivers/Impact: Development of an active target (time projection chamber type target + detector combination) and a high resolution magnetic spectrometer for R3B. The active target will require sophisticated readout building on the expertise of the Daresbury Nuclear Physics Group (NPG) and RAL. The DESPEC upgrade would involve the construction of planar germanium gamma-ray detectors, for which the UK has significant expertise. ILIMA would involve the development of super-high-gain Schottky pickup devices for improved single-ion detection in the collector ring (CR).

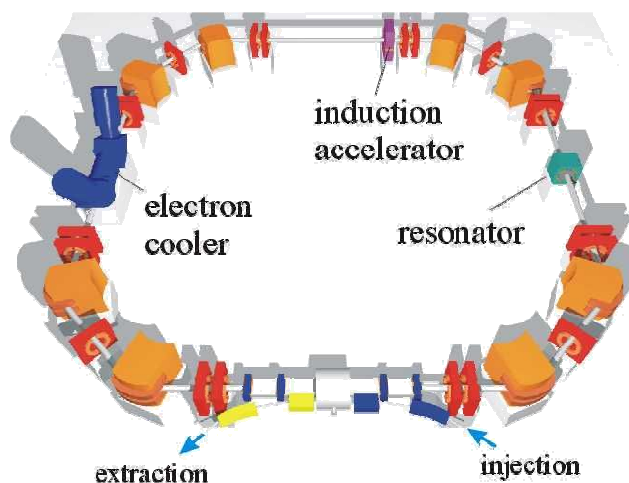
Institutions: 8. ***Academics:*** 16

4.2.1.2 ISOL-SRS

The ISOL-SRS project is a major component of a wider European initiative that will exploit the heavy-ion storage-ring facility, TSR, to be installed at the HIE-ISOLDE radioactive-beam accelerator at CERN – through the CERN subscription the UK also subscribes to ISOLDE. This is a joint collaboration between CERN, Germany, UK and Belgium. The storage ring is being relocated from MPI, Heidelberg. The UK collaboration will lead the development and construction of advanced, innovative detector systems for experiments on the TSR. This will be a unique facility worldwide - utilising a vast range of isotopes injected

into the ring at energies ideal for studies of nuclear phenomena. It will provide unrivalled opportunities for measuring key reactions and properties of nuclei relevant for nuclear astrophysical processes, and measuring single-particle, collective, and ground-state properties of the nucleus essential for the understanding of the interactions between nucleons in exotic nuclei, at both the precision and intensity frontiers. The main goal of the project is to build a spectrometer for the measurement of charged-particle reaction products both in-ring and external to the ring (Helical Orbit Spectrometer), each employing

The heavy-ion storage ring to be installed at HIE-ISOLDE.



high granularity silicon-detector systems. The two detector systems will enable the whole range of radioactive nuclei accelerated by HIE-ISOLDE to be studied with unsurpassed energy resolution and sensitivity, taking advantage of the superior properties of the radioactive beam cooled within the ring. The key advantage of a storage ring is that the beam passes through the target, within the ring, multiple times. This effectively boosts the beam intensity by a factor which is equivalent to the number of passes – importantly increasing the range of physics accessible at the ISOLDE facility. The detection system within the ring will be a silicon array adapted for UHV conditions.

The Helical Orbit Spectrometer, outside the ring, is based on a highly novel approach, developed in the US – with UK involvement - (called HELIOS), to build a detection system in which reaction products are transported in helical orbits from the target to the detection system. This provides enhanced resolution and large solid angle coverage. It should be noted that the spectrometer can be operated even without the construction of the ring and is viewed by many as a significant breakthrough in the ability to performed high resolution nucleon-transfer measurements.

Science Reach: What are the Origins of the Elements? What are the key reaction processes that drive explosive astrophysical events such as supernovae, and X-ray bursts? What are the nuclear processes, and main astrophysical sites, that produce the γ -ray emitting radionuclides observed in our galaxy? How do nuclear reactions influence the evolution of massive stars, and how do they contribute to observed elemental abundances? **What is the Nature of Nuclear Matter?** What are the limits of nuclear existence? How do simple patterns emerge in complex nuclei? Can nuclei be described in terms of our understanding of the underlying fundamental interactions? What is the equation-of-state of nuclear matter? How does

the ordering of quantum states change in extremely unstable nuclei? Are there new forms of structure and symmetry at the limits of nuclear existence?

Scientific Leadership: Physics co-ordinator and deputy Scientific Spokesperson within the ISOL-SRS collaboration. Members of the HIE-ISOLDE Steering Committee and Physics Coordination Group. Chair the INTC (ISOLDE and Neutron Time-of-Flight Committee) and members of the CERN Research Board. Excellent track record of obtaining beam time at ISOLDE and performing experiments at other ISOL facilities. Experience in using storage rings and helical spectrometers and constructing state-of-the-art silicon detection systems. World renowned scientific leadership in nuclear astrophysics, transfer reactions, coulomb excitation, laser spectroscopy.

Technological Expertise/Drivers/Impact: Key development will be the development of silicon detectors and electronics capable of operating in UHV environment (inside the storage ring) – this could create technological leadership. The development of the helical spectrometer will benefit from the current UK programme to modify an existing NMR magnet obtained from Nottingham to create a first generation helical spectrometer for ISOLDE.

Institutions: 8. Academics: 32

4.2.1.3 AGATA-upgrade

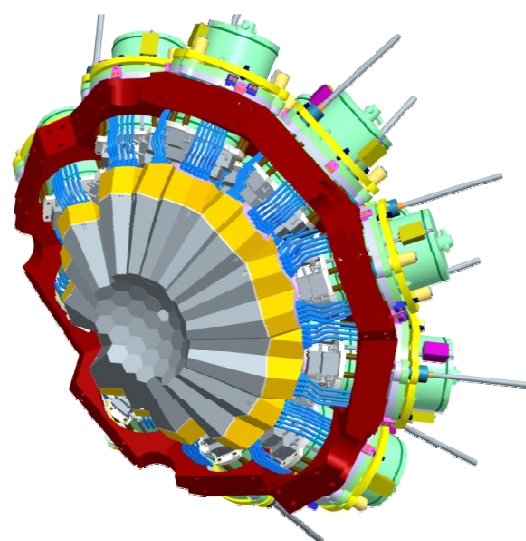
High-resolution spectroscopy is *the* most important tool for understanding nuclear structure. AGATA is the only major high-resolution gamma-ray detector being developed in Europe. It is seen as one of the key spectrometers by the Physics programmes of all the major large-scale facilities.

A key feature of this spectrometer is its ability to track the gamma-rays as they pass through the germanium detectors. This highly complex process is achieved by processing the charge developed on multiple electrodes which is then compared with detector characterisation maps. This advance has the potential to transform gamma-ray spectroscopy and makes the device universally important to physics programmes across Europe.

The demonstrator phase has already been used at Legnaro and is currently being re-configured for use with relativistic beams at GSI from 2012-14. A key goal of the international community is to increase the number of detectors in AGATA over a period of time. This will make significant improvements to the sensitivity of the instrument and open up new physics programmes not only at the laboratories mentioned above but also at the new facilities such as GANIL (SPIRAL2), CERN (HIE-ISOLDE) and FAIR.

In this project the UK will use its internationally recognised strength to provide leadership in the **mechanical** design of the detector holding structures, development of the front end **electronics**, detector characterisation and pulse shape analysis development, the mechanical and electrical design of the

Schematic figure showing an upgraded version of AGATA which will be used in experiments at various facilities in Europe.



detector cryostats as well as make a contribution to the capital costs. These developments will build on the exiting demonstrator (phase 1) construction creating a device with greater solid angle and a significantly enhanced science reach in terms of improved sensitivity.

Science Reach: *What is the Nature of Nuclear Matter?* What are the limits of nuclear existence? How do simple patterns emerge in complex nuclei? Can nuclei be described in terms of our understanding of the underlying fundamental interactions? What is the equation-of-state of nuclear matter? How does the ordering of quantum states change in extremely unstable nuclei? Are there new forms of structure and symmetry at the limits of nuclear existence?

Scientific Leadership: The UK is preeminent in the construction and design of state-of-the-art gamma-ray spectrometers. Many of the key developments in this field originate from the UK community. The UK holds central positions within the AGATA collaboration: spokesperson and chair of the AGATA collaboration council, chair of steering committee, membership of management board. Strong leadership in terms of developing the scientific programme, a significant fraction of the science programme of AGATA has a UK spokesperson.

Technological Expertise/Drivers/Impact: UK played a leading role in the development of phase 1 (demonstrator) development and construction. The community have been central in detector characterisation, electronics and instrumentation development and mechanical design. The novel approach to gamma-ray detection has already spawned a number of applications of the technology including medical and homeland security. There is significant potential for further applications.

Institutions: 6. Academics: 14

4.2.2 Funding Consequences

The UK has heavily invested in FAIR/NuSTAR as this will be the premier fragmentation facility in the world. For the nuclear physics programme at FAIR the UK has leadership in the key projects. There is a strong argument for building on this to enhance the scope of the equipment being built to maximise the scientific return. Again lack of future funding will weaken the UK's position substantially – particularly at a time in which Associate Membership is being negotiated.

The AGATA collaboration is building the world leading gamma-ray spectrometer. The UK's contribution results from UK leadership in both the science programme and the design and construction of such devices going back 20-30 years. Worldwide the UK is recognised as having a number of leaders in the science of gamma-ray spectroscopy and the leading engineers who develop the spectrometers and instrumentation. Lack of funding for the AGATA upgrade will weaken the scientific leadership and a technological area which has important applications for medical imaging and homeland security.

A significant community has grown around the ISOL-SRS project. The UK has now established leadership in the storage ring at ISOLDE in recognition of the great scientific potential. This investment will deliver high quality science in the short term during the hiatus in which NuSTAR is being built. Lack of funding for this project would remove a key opportunity to take leadership in ISOL science, an area in which there is likely to be significant future funding with the construction of a major European ISOL facility; EURISOL.

4.2.3 Longer Term Directions in Nuclear Structure and Nuclear Astrophysics

The current developments associated with the ISOL facilities at ISOLDE (HIE-ISOLDE) and GANIL (SPIRAL2) are vital stepping stones which are required if the UK is to have a genuine involvement in the premier future ISOL facility, EURISOL. It is believed that this project will not occur until well into the 2020s, perhaps closer to 2030, and requires significant international partnership. The precise form of EURISOL is unclear and it could end up being based at laboratories such as GANIL or CERN. Alternatively, the ISOL@MYRRAH project in Belgium may be a future direction for the UK. However, between the construction of EURISOL and the current generation HIE-ISOLDE and SPIRAL2 there are expected to be upgrades; (1) the upgrade of the CERN injectors, to be ready after the second long shutdown close to 2020 (new 160 MeV linac and increase of energy of PS Booster to 2 GeV) that will provide approximately a factor of 10 intensity of HIE-ISOLDE beams; (2) the provision of high-intensity fission beams from SPIRAL-2, probably on the same time-scale.

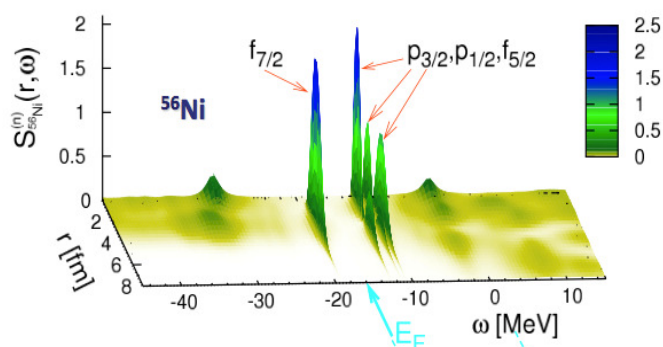
In addition to the future radioactive beam facilities at FAIR and EURISOL, the NuPECC⁴ long range plan published in 2010⁵ gave “Very strong support for existing and future stable-ion beam facilities”. This would be a high intensity frontier for the subject requiring a significantly new approach to detection systems with associated technological challenges, but opening up the potential for the study of highly exotic phenomena in stable nuclei. A potential candidate for such a facility is ECOS⁶ (European Collaboration on Stable beams).

4.3 Overview of Nuclear Theory research in the UK:

UK research in Nuclear Theory provides internationally-recognized, high quality research and covers a broad spectrum of topics, despite its objectively small size. These range from the nucleon structure (and links to the underlying theory of QCD), through to the highly complex subject of nuclear reactions. With the recent addition at Surrey of a program involving the structure of exotic nuclei and nucleonic matter, the UK now aims at playing a world-class role in most major aspects of the subject. It should be noted, that some aspects of the UK’s hadronic physics programme overlap with research questions addressed by the LatticeQCD community.

Links to the underlying theory of QCD are being explored by the Manchester group which has a strong interest in chiral symmetry and the role it plays in the structure and interactions of hadrons. Effective Field Theories (EFTs) where the strong interaction is

Theoretical spectral function for ⁵⁶Ni predicted from chiral EFT interactions. This shows the spatial and energy distribution of neutrons in the system that can be tested through knockout measurements. Phys. Rev. Lett. **103**, 202502 (2009)



⁴ The Nuclear Physics European Collaboration Committee

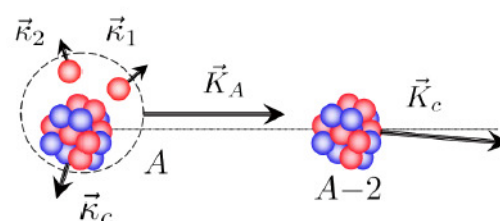
⁵ http://www.nupecc.org/lrp2010/Documents/lrp2010_final_hires.pdf, http://www.nupecc.org/lrp2010/Documents/lrp2010_booklet_final.pdf

⁶ <http://www.nupecc.org/ecos/ECOS-Final.pdf>

grown from the underlying QCD and renormalization group methods allow the accurate determination not just of static properties of nucleons but also their responses to electromagnetic fields. Three-body forces between nucleons arise naturally within these theories and are now known to be crucial to the description of nuclei from first principles. Moreover, the framework can bridge the gap between quantities measured in experiment and those determined from lattice simulations of QCD.

“Ab-initio” nuclear structure aims at achieving predictive power in computation at the limits of stability. Advances in theory and computation capability now offers the possibility for the calculation of nuclear properties from realistic nuclear forces for atomic masses of $A=60$ and above. Coupled cluster and many-body Green’s function theories are developed in Manchester and Surrey. New, UK-led, breakthroughs have extended these methods to truly open-shell isotopes, *de facto* increasing the number of tractable isotopes from few tens to several hundreds. Time dependent approaches are being devised and exploited to study heavy-ion reactions and gain insight into the equation of state of nucleonic matter.

Nuclear correlations and properties of asymmetric nuclei are studied through nucleon addition and removal. Both the eikonal (Glauber) approximation of knockout reactions and the theory of (p,d) and (d,p) transfer processes are actively developed, covering wide ranges of energies. Further aims are to achieve accurate description of various reaction tools as well as reliable descriptions of astrophysical reaction rates. Established strong collaborations with world leading facilities and on experimental data are paving the way to answering fundamental questions on the structure of nucleonic matter and confront results from *ab-initio* theories.



Schematic of a knockout whereby two (red) nucleons in the projectile (left) are knocked out in a collision with a target (right). Phys. Rev. Lett. **102**, 132502 (2009)

[Science Reach: How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions? What is the Nature of Nuclear Matter? What are the Origins of the Elements?](#)

[Scientific Leadership: The UK has a strong international reputation in reaction theory and is building a leadership on ab-initio approaches. Given the growth of experimental programmes associated with exotic isotopes and on properties of nucleonic matter, future challenges will involve bridging structure and reaction theory in a consistent way that allows extracting meaningful information from data.](#)

[Institutions: 2. Academics: 7](#)

5 Status of Nuclear Theory in the UK

With significant quantities of high quality data expected from current and future experiments reaching into new territory, Nuclear Theory has the threefold mandate of providing *leadership in the subject*, developing *new, highly sophisticated, models and computational techniques* and aiding in the *interpretation of new data*. Leadership implies strong independent programs that can impact the field of nuclear physics.

Despite the quality of the theory programme, highlighted in section 4.3, the potential for scientific leadership and support of the experimental community is hindered by the small size of the Theory Community (already at the minimum for good coverage of the field). The current number of tenured staff is 7. There is a strong imbalance between experiment and theory positions of 8:1, with theory concentrated at only two institutions. This is in sharp contrast to other leading countries in Nuclear Physics research such as France, Germany and Italy, where this ratio is 4:1, or better.

A recent IoP examination of the health of UK Nuclear Physics⁷ indicates the need of increasing the Theory Community, for example, to maintain leadership in Nuclear Physics and to train the next generation of scientists through a national graduate programme. There are strong concerns about the size of the Community which is too small to provide quality support to the wider experimental community and to develop new, far-reaching theoretical methods.

5.1 Future requirements and priorities:

Stronger interactions are needed between Theory and the rest of the UK community and this would require financial underpinning. For example, although the theory community possesses experience in structure and reactions that overlap strongly with the UK's experimental programme, there is only limited theory-experiment interaction due to a lack of resources. UK theory is not guiding UK experiments, and the situation will not improve without structured theory PhD courses.

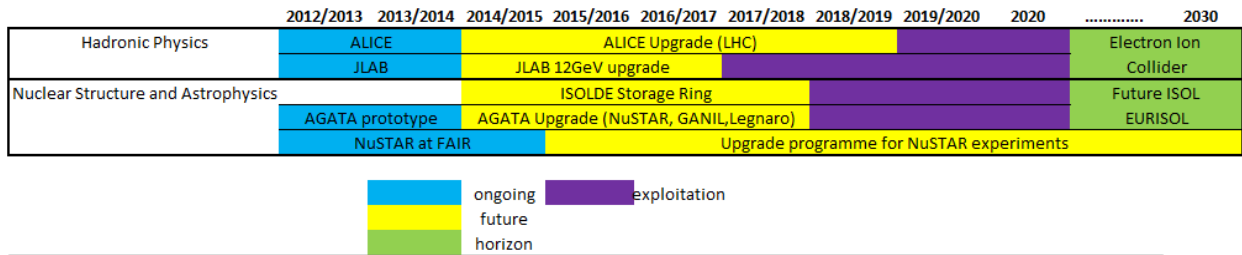
In order to support the existing community there should be a prioritisation for support through appropriate levels of postdoctoral posts and research studentships. Major new initiatives (with UK leadership) are only possible if this support is present, together with the necessary resources for travel and collaboration, and access to high performance computing (HPC). Cutting edge theory requires continuous collaborations with international researches and teams at overseas facilities, UK theory involvement requires the same level of mobility/involvement as the experimentalists. As experiments are carried out by international teams on overseas facilities, UK theory involvement requires the same level of mobility/involvement as the experimentalists.

Beyond this, the highest priority of the Nuclear Theory Community is the creation of new theory groups – a recommendation of the IoP report⁷. The community believes that there should be a competitive process in which STFC funds 50% of a chair. This should be bid for, with matching funds, by UK Physics departments with NP groups. This would be at institutions other than Surrey and Manchester – which already host theory groups. STFC funds should be for an initial period of 5 years.

6 Time Line and Science Roadmap

The current NuSTAR construction project runs until 2015. Much of the equipment being developed will have been used in measurements at the existing GSI facility, thus testing the equipment or developing techniques. By 2015 the completed components will have been delivered to FAIR and construction will be complete, and the exploitation phase will commence. **Exploitation with the full FAIR facility will commence in 2018.**

⁷ IoP report on the Health of UK Nuclear Physics, "A Review of UK Nuclear Physics Research", October 2012. http://www.iop.org/publications/iop/2012/file_58792.pdf



The above chart outlines the timelines for the on-going projects as well as the possible future projects. Projects labelled horizon correspond to those which will form part of the UK's programme beyond 2020.

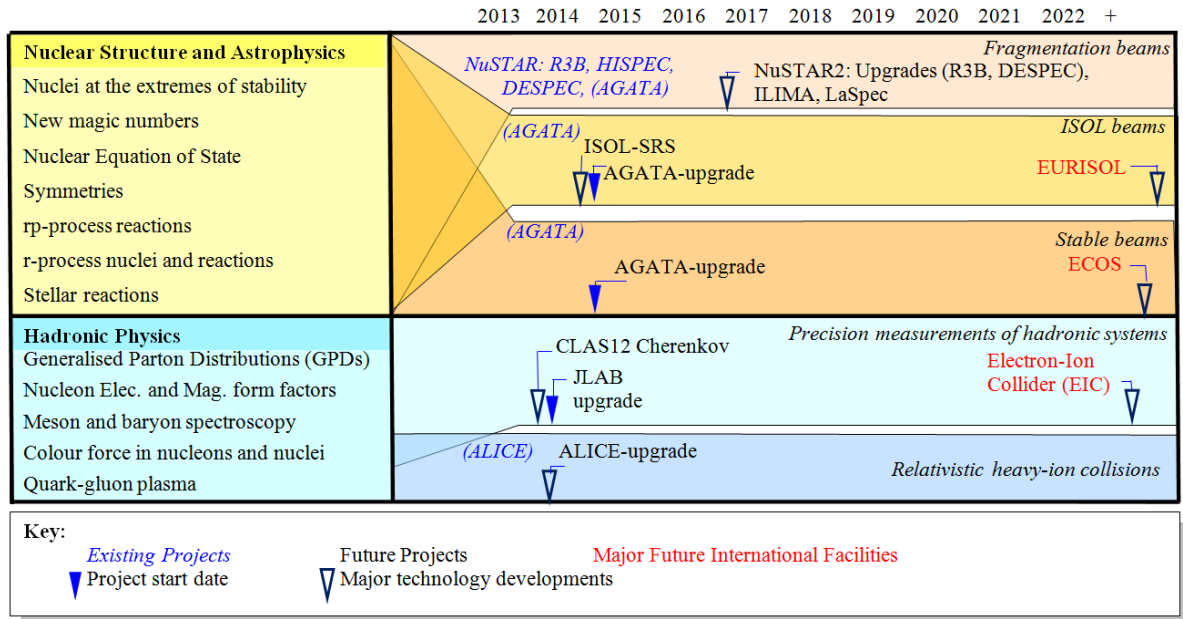


Figure 1. The nuclear physics road map illustrating the connection between science themes and the projects, past present and future.

During the period 2013-2018 it is absolutely critical that a number of projects are funded in order to maintain the scientific expertise and leadership within the community.

The diagram in Fig. 1 provides a map connecting the scientific areas of “nuclear structure, nuclear astrophysics” and “hadronic physics” and current and future projects. Projects associated with major technological challenges (some of these are discussed in section 7) are indicated (see the key for details).

7 Impact and Technology Roadmap

Beyond the value of the science of the UK nuclear physics community, there is significant added value in terms of their strong links to the nuclear energy industry and the development of detection technologies which reach into medical imaging and homeland security. This marks them out above other STFC communities.

7.1 Impact

Historically, Nuclear Physics has made important contributions to applied science. The first accelerators were developed to study nuclear phenomena and proton and carbon beam cancer therapy has been driven largely by the international Nuclear Physics community. Many of the detection systems used for medical imaging also have their origins in nuclear physics research. The community continues to exploit developments in detector technology being made for research in applications. For example, several groups including Daresbury and Liverpool have a number of projects (some funded through the STFC IPS scheme) to utilise advances in the instrumentation of Cadmium-Zinc-Telluride (CZT) and Germanium detectors for imaging and scanning applications in medicine, nuclear decommissioning and homeland security. Projects include Distinguish, PorGamRays (highlighted in the STFC “A new vision for new times” vision document), SmartPET, ProSPECTus, ScrapProbe, GAMMAKEV.

The UK nuclear physics groups such as Manchester (Dalton Institute), Birmingham (Centre for Nuclear Education and Research), Liverpool and Surrey have also been the custodians for aspects of the UK’s longstanding research and educational programmes linked to the nuclear industry. In the revitalisation of the nuclear industry in the lead up to the construction of new nuclear power stations, and the decommissioning of the old ones, these groups have grown their research and educational programmes. These strongly link technology development in instrumentation, materials, chemistry, geology and biosciences and as such have significant potential for the development of applied science across the disciplines. This leadership is strongly recognised also outside the STFC, e.g. within EPSRC and BIS.

7.2 Technology Roadmap

The UK Hadron physics community, concentrated at the Universities of Edinburgh and Glasgow, is the development of particle identification detectors and applications requiring fast timing. The UK groups involved in relativistic heavy ion reactions are based in Birmingham, Liverpool and STFC Daresbury. These groups have a strong background in the development of complex trigger electronics and semi-conductor tracking devices.

The UK Nuclear Structure Physics community relies on access to high intensity stable and first generation radioactive ion beam facilities. The physics programmes require the use of high resolution gamma-ray spectrometers, fast timing capable scintillators, charged particle and neutron detector systems. The UK makes a world leading contribution to the instrumentation in all of these areas. The community has particular strengths in the design and build of high purity germanium detector systems through projects such as AGATA, the design and build of granular semiconductor based charged particle detector arrays utilising ASIC readout through projects such as AIDA (part of NuSTAR) and fast scintillator systems through the NuSTAR and PARIS collaborations.

Both the Nuclear Structure Physics and Nuclear Astrophysics communities utilise the world’s leading radioactive ion-beam facilities. Their future physics programme requires the use of significantly more intense radioactive beams. This leads to the requirement for high density detection systems capable of exploiting the higher intensity beams, while maintaining the strict energy, position and time resolution performance characteristics required to deliver the physics programme. Both communities recognise the importance of access to future storage ring facilities and the associated technology projects necessary to support this activity.

It is expected, that the future projects in both fields will use the existing strength and world-leading reputation of these groups in the development and construction of new detector systems. Directly following from this, a number of key technologies enabling the UK community to maintain or develop leadership can be derived:

- **Photon detection in the presence of strong magnetic fields with single photon sensitivity and excellent timing:** The experiments which are at the centre of current and future studies in hadron physics require tracking, particle identification and calorimetry frequently inside strong magnetic fields. As scintillation and Cherenkov counters are the most heavily utilised experimental techniques, all requiring the detection of visible or near-UV light, often with single photon capability at high rates and with excellent timing resolution, the development and construction of photon detection devices fulfilling these specifications is at the centre of future developments and a particular strength of UK NP groups and UK industry. Promising current and future developments aiming at ps timing resolution, being pursued by UK NP groups, include photomultiplier tubes built from microchannel plates with protective layers made by atomic layer deposition, the replacement of classic amplification structures with diamond coated microstructures, position sensitive cathodes with RF structures for excellent timing resolution and a vibrant research programme in semi-conductor photo detection devices. The UK is also planning to develop gamma-ray detection in a high magnetic field, NMR, environment. All of which provide a crucial enabling technology for future detector systems in nuclear and particle physics with a large number of potential applications in healthcare, security together with other industrial applications.
- **Fast scintillating materials with excellent granularity and energy resolution:** Organic and inorganic scintillation materials are frequently the materials of choice for time-of-flight measurements, particle identification and calorimetry. They are used in a wide range of nuclear and particle physics experiments as well as in a large variety of medical and industrial applications. While the bulk of applications is driven by established materials, new applications require novel materials or established materials produced in new shapes (e.g. as fibres from inorganic materials). These materials open up applications for highly granular detector systems with excellent position and energy resolution. UK NP groups are moving from being users of established materials to playing a more active role in the development of new materials, e.g. via participation in the CrystalClear collaboration at CERN.
- **Cherenkov radiator technology and imaging optics:** The momentum range of modern hadronic physics experiments is ideal for a variety of imaging Cherenkov counters to be used for particle identification. The opening angle of the cone of light created by a charged particle passing a dielectric medium, faster than the speed of light within this medium, is a direct measure of the particle's velocity. Combined with an independent momentum measurement, this provides a powerful tool for particle identification. The photon detection requirements for Ring Imaging Cherenkov counters (RICH and DIRC) are met by the devices described above. The other crucial technologies are the design and construction of a suitable radiator material, the understanding of photon transport and an optical imaging system concentrating the Cherenkov cone onto a focal plane equipped with photon detection devices. UK NP groups are involved in the RICH detector for the CLAS12 upgrade at Jlab (see section 4.1.1.1), the DIRC detectors for the PANDA experiment at FAIR and the planned forward PID based on both technologies for the future EIC detector system (section 4.1.3). It should be noted that the world-leading technologies developed in UK NP groups are also considered for several PP experiments.

- **High count rate tracking devices:** This development is driven by the needs of the planned upgrade of the ALICE detector at CERN where the UK is proposing to play a leading role in the upgrade of the inner tracking system, based on their world leading expertise in the development of Monolithic Active Pixel Sensors (MAPS) and trigger development (section 0).
- **Diamond detectors:** Detector systems based on industrial diamond promise to be both fast and radiation hard, offering a huge potential for future applications. UK NP groups are rapidly building up expertise in the development and construction of diamond based detector systems. For example, through the HISPEC component of the NuSTAR project (section 4.2.1.1) considerable expertise and leadership in the development and design of fast timing from diamond detectors has been developed at York and Surrey.
- **ASICs for nuclear spectroscopy:** Highly granular silicon based charged particle detector solutions are required for example in the R3B and DESPEC projects within the NuSTAR collaboration. The UK is responsible for both the design and build of semiconductor detectors and the development of the ASICs for these projects.
- **Germanium tracking detectors:** The AGATA project has pioneered the development of highly granular high purity germanium detector solutions. The community is now pursuing the development of compact granular planar germanium detector systems for applications such as the DESPEC detector array within the NuSTAR collaboration. The UK has established the capability to fully assemble the cryogenic detector heads (through the ProSPECTuS project) necessary to realise a future array. The community is also investigating the application of point contact germanium detector technology to facilitate extremely high-resolution gamma-ray spectroscopy from large volume germanium diodes (through a recent IPS project). Such detectors would have a wide variety of applications in focal plane detector systems.
- **Neutron time of flight:** The Manchester and York groups have joined the nToF collaboration at CERN which uses neutron time-of-flight to measure cross-sections for neutron capture and neutron-induced fission both for reactions of astrophysical interest and for isotopes of interest to present and future fission reactor cycles. The funding for this work comes from EPSRC under the "Keeping the nuclear option open" programme and currently supports two PhD students taking data at nToF.
- **Decay heat:** As witnessed in Fukushima understanding the heat produced in the radioactive decay of fission products is extremely important. A significant fraction results from beta-decays. But in order to understand the energy deposition the feeding patterns need to be identified, the UK have been involved in total absorption measurements to resolve longstanding issues: Phys. Rev. Lett. 105, 202501 (2010).
- **UHV compatibility:** The future EXL project at FAIR and the storage ring at HIE-ISOLDE require the development of UHV capable detector systems. The performance of room temperature semiconductors such as silicon and Cadmium Zinc Telluride (CZT) can be improved upon by cooling the crystal and preamplifier electronics in order to reduce the thermal noise and leakage current observed in the system. Cryogenic operation also facilitates the use of these sensors in an Ultra High Vacuum (UHV) environment. The key requirements are: (i) To achieve an energy resolution of <2keV that is ideally required for future electron spectroscopy applications (ii) To minimise the out-gassing of the detector sensors so they can be operated in a UHV environment.

The technologies outlined above rely on expertise in the design and construction of fast electronics systems for signal processing, data acquisition and control systems, for which there is also significant expertise within the UK NP groups (e.g. within the Daresbury NPG).

Furthermore, the UK is also the home of specialist technologies and expertise in a number of different areas. For example, the nuclear physics group at the University of Glasgow is one of the world's leading groups in the production and characterisation of highly polarised high energy photon beams using Bremsstrahlung from suitably oriented diamond radiators. This technology is instrumental e.g. for the GlueX and CLAS experiments at JLab.

8 Funding

The current NuSTAR project is funded at a level of £7.4M over 5 years, which equates to an average level of funding of approximately £1.5M/year. This compares with £3.1M/year funding for the exploitation programme through consolidated grants⁸. (Total funding in grants line including funding of the Daresbury Nuclear Physics Group (NPG) and subscriptions etc... is £4.9M/year). This current level of funding resulted in approximately only 45% of the research themes associated with consolidated grant applications being completely funded (26% of the themes, whilst still being very high quality science judged against projects in the international sphere, had no funding at all) and consequently a significant fraction of the community being without underpinning research funding. The last grants round left nuclear physics severely depleted in PDRAs and a significant fraction of the community unfunded. This coupled with the 30% reduction in STFC studentships is having a serious impact on the subject which sees it in a vicious

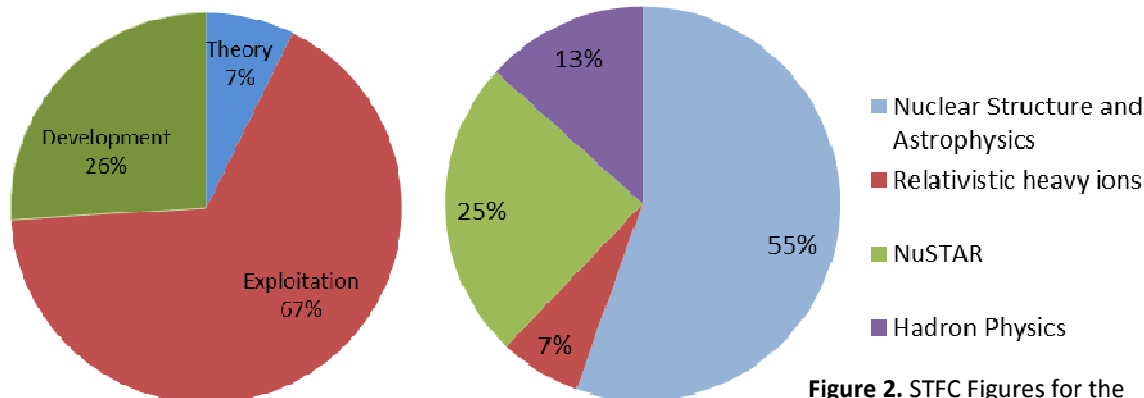


Figure 2. STFC Figures for the breakdown of Nuclear Physics funding

circle of decreasing resource – smaller numbers of students and PDRAs leads to diminished international competitiveness and poorer research performance, decreased ability to compete for grant income, and consequently fewer PDRAs and students, etc. A modest increase in support could help reverse this trend.

The recent IoP report into the health of Nuclear Physics⁷ has, once again, highlighted the fact that funding for the subject has dropped – in 2007 funding for research was ~£8.5M/year which has fallen to a level of £6.4M/year for the period 2011-2015.

⁸ Source: STFC grants on the web

Project and grant funding at the current level is significantly below that required for a sustainable research programme and is resulting in long term damage to the reputation and morale of the community which may be irreversible if not remedied in the immediate future.

8.1 Balance of Programme

The funding for nuclear physics (Fig. 2) is currently divided 1/4 projects (or development) and 3/4 exploitation (incl. theory). Approximately three quarters of the exploitation component is associated with nuclear structure and nuclear astrophysics with the remainder being linked to hadronic physics (ALICE and JLab, etc). This latter distribution broadly reflects the size of the respective communities and is thus appropriate in terms of maintaining overall scientific leadership in these areas. However, in order to ensure the vitality of the two components of the programme both exploitation and project funding is required in “hadronic physics” and “nuclear structure and astrophysics”.

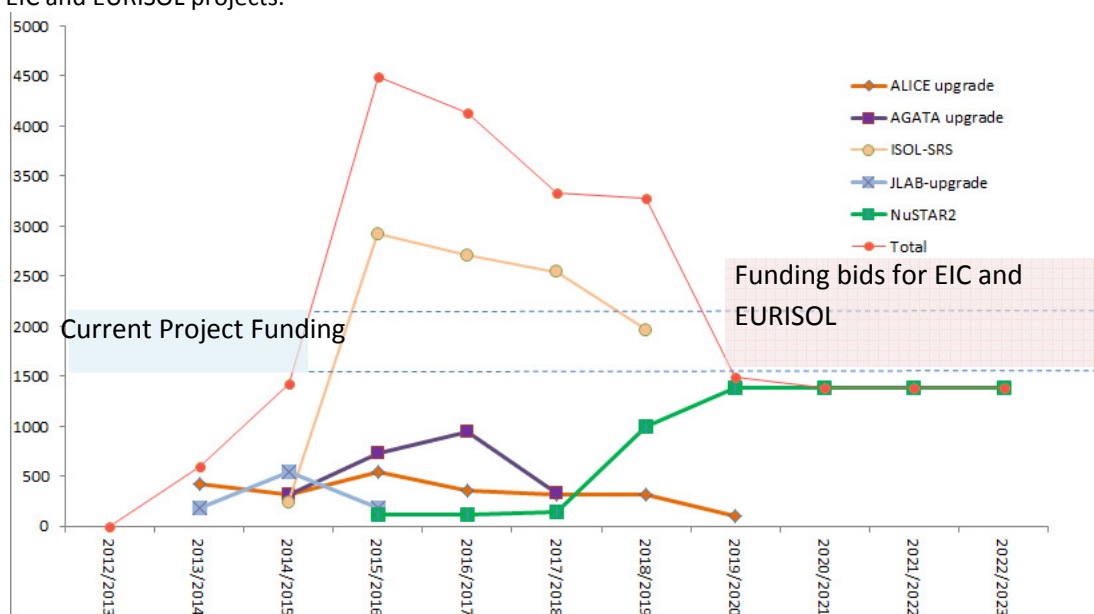
The optimal balance between project development and exploitation would be one in which the exploitation component should be 2/3 and projects 1/3. Both streams are currently underfunded.

8.2 Funding Profiles of New Projects

	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022	2022/2023	Total
ALICE upgrade		421	321	541	356	316	316	107				2375
AGATA upgrade			315	730	950	335						2330
ISOL-SRS			240	2920	2710	2540	1960					10370
JLAB Upgrade		183	549	183								915
NuSTAR2				120	120	140	1000	1380	1380	1380	1380	6900
Total/year		604	1425	4494	4136	3331	3276	1487	1380	1380	1380	22890
Hadron Physics		604	870	724	356	316	316	107	0	0	0	3290
Nuclear Structure and Astrophysics			555	3770	3780	3015	2960	1380	1380	1380	1380	19600
Current projects(NUSTAR)	2284	1609	1532									

Table 1. Funding profiles for nuclear physics projects.

Figure 3. Funding profiles (k£) for future nuclear physics projects. The current level of project funding for NuSTAR is indicated by the shaded blue band. Beyond 2019 strong the UK would be expecting to participate in the EIC and EURISOL projects.



The funding profiles for the NuSTAR project and the future projects are shown in table 1 and Figure 3. It should be noted that these funding profiles have been developed through cross community consultation in which the project costs and spend have been optimised to ensure balance and breadth of programme. Moreover, the funding for many of the projects would draw on the cross-community nuclear physics support group. For example, the ISOL-SRS project would for the four years between 2014/15 and 2017/18 have a spend profile of £240k, £920k, £660k and £550k for cross-community posts. At present no attempt has been made to re-profile the AGATA spend, but there is flexibility to do so. Beyond 2019 the UK would be expecting to participate in the Electron Ion Collider and EURISOL projects. It is not possible to realistically gauge the level of investment, but this will require a level of funding above the existing 2012 level.

This has been challenging due to the hiatus in project funding for nuclear physics resulting in a number of overlapping projects with an urgent short term need for funding – these cover the areas of hadronic physics (JLAB and ALICE) and nuclear structure and astrophysics (AGATA, ISOL-SRS). In the longer term, there is only the NuSTAR2 project which does not significantly overlap with the other four. However, funding for EURISOL and EIC involvement will likely be required on these timescales.

It is evident that a significant increase in project funding is essential if the breadth of the nuclear physics programme is to be supported.

9 Priorities

The 5 projects described here all should be considered to be major projects which would compete with the best nuclear science internationally and all have the potential to have a significant impact in terms of science – this should be borne in mind when establishing the ranking of nuclear science projects against those in other subjects. All have significant UK leadership but are major international collaborations, provide scientific impact which will be at the cutting edge of the subject leading to high impact publications, and will require significant advance in detector technology or instrumentation.

Funding across the spectrum of the science programme is a priority. Within hadronic physics there has been significant cooperation between the JLAB and ALICE upgrade groups. There is a view that rather than prioritising between the two projects there should be a funding stream which supports both – this level of investment would be between £107k/pa and £870k/pa.

Similarly, the ISOL-SRS project spend has been re-profiled to accommodate spend profiles of other NP projects (and an updated Sol submitted). The NuSTAR2 project will not commence until the current NuSTAR build is complete (2015) and as a consequence does not start in earnest until 2018/2019. At this stage the spending on ISOL-SRS drops to zero. In this way the two projects do not compete directly for funding. As with the hadronic physics theme, there is not a need to prioritise between these two projects. Within the nuclear structure and astrophysics theme only the ISOL-SRS and AGATA project overlap. Both of these provide the UK community with high impact science in advance of the start of NuSTAR.

In order to gauge the community priorities, a vote was taken to evaluate the leading projects in the two categories i) hadronic physics and ii) nuclear structure and astrophysics. Since there was a strong belief that a balanced programme was required the community did not prioritise between these areas. The community were asked to consider “scientific impact, scientific leadership, technical leadership and how the UK can maximise its position internationally”⁹. There were responses from about 3/5 of the

⁹ The scoring system used 1 for highest priority, 2 for next..... then average scores were computed.

community – those in the hadronic physics community abstained, strongly believing that the ALICE and JLAB upgrade projects should be considered as a single scientific endeavour and hence prioritisation was not appropriate. This is a reasonable position to adopt and indeed should also be applied to the three nuclear structure and astrophysics projects – funding has been adjusted such that in principle all should be funded. This would be the view of the nuclear physics advisory panel (NPAP). Nevertheless the poll indicates a preference for the JLAB upgrade over that of the ALICE upgrade, by those outside that sub-community, and the ISOL-SRS is favoured slightly over NuSTAR2 and ahead of AGATA. Of course a significant element of this will relate to the number of people involved with each project. However, this grouping of academics around projects in part already reflects the scientific and leadership opportunities they present.

The panel would like to re-emphasise that substantial effort has been made to ensure that the timing of the projects has been adjusted to fit together to produce a coherent science programme, optimise scientific and technical leadership and maximise scientific return for the UK.

10 Appendices:

10.1 Nuclear Structure and Reactions programme

What is the Nature of Nuclear Matter?

- What are the limits of nuclear existence?
- How do simple patterns emerge in complex nuclei?
- Can nuclei be described in terms of our understanding of the underlying fundamental interactions?
- What is the *equation-of-state* of nuclear matter?
- How does the ordering of quantum states change in extremely unstable nuclei?
- Are there new forms of structure and symmetry at the limits of nuclear existence?

The atomic nucleus remains something of an enigma. How precisely does the observed regular ordered behaviour emerge from the ferment of the complex many body interactions of the nucleons? How does the manifestation of the strong interaction on the nuclear scale emerge from the properties of QCD and how does this impact on macroscopic nuclear properties? Is the nature of nuclear matter in systems that as yet are only created in the most extremes of environments, such as supernovae, completely different to that already studied in the laboratory?

Unlike questions of existence which have recently featured strongly in particle physics, the answer to the above cannot be arrived at in a single set of measurements – the answer is not yes/no. Rather, it involves building a picture using a whole sequence of measurements using a range of probes, at different types of experimental facilities. It is not until all the pieces are in place that the understanding is complete. Some of these facilities are new generation radioactive beam facilities, such as NuSTAR at FAIR in Germany, RIBF at RIKEN in Japan, HIE-ISOLDE at CERN, SPIRAL2 in France and the FRIB facility currently being constructed in the US. In addition a range of other facilities are required, some of which accelerate stable nuclei. This scientific methodology necessitates a significant exploitation programme.

Some elements of the picture are in place, for example there is a good understanding of nuclear matter and nuclear structure close to stability. Here fundamental properties such as masses, spins and moments have been determined, their single-particle and collective characteristics established and models tuned. However, as new experimental facilities have been developed the established understanding of nuclei and nuclear matter have been challenged and eroded. It is observed that the single-particle levels which arise from solutions to the Schrödinger equation for the nuclear potential are not immutable – they evolve as a function of the neutron to proton ratio. This means that nuclei which were believed to correspond to magic numbers away from stability, do not. Such an evolution yields an insight into the behaviour of the strong interaction within nuclei. This has consequences for the relative stability of exotic proton and neutron-rich nuclei and the synthesis of elements in cataclysmic stellar processes. Nuclei close to the limits of stability challenge our long established view. As neutrons are added to a nucleus there comes a point that even though there is only an attractive interaction (there is no Coulomb repulsion) the last added neutron will not bind/stick to the nucleus. Understanding the point at which this happens reveals much about the nature of the strong interaction. It is at the point, which is called the neutron drip-line, that neutron and proton matter can decouple, the neutrons becoming much more extended in what are

called halo nuclei. In these systems there is typically a core of normal nuclear matter embedded in a cloud of neutron matter. This gives rise to exotic properties such as the oscillation of the core against the halo neutron(s). The latest experimental facilities allow nuclei at the drip-lines to be studied with great precision and even probe the nature of nuclear matter to unbound nuclei beyond the drip-lines. It is in this paradigm that nuclear matter is yet to be understood. The techniques being developed by the UK and others will allow the wave-functions of the nucleons in these most exotic nuclei to be precisely measured providing an insight which has to this point been missing. In all of these areas the UK is playing a leading role.

Nucleonic superfluidity, which results from interactions between pairs of neutron or protons or indeed a neutron and a proton, plays a major role in nuclear structure. Indeed in loosely-bound nuclei, pairing may be the key factor for stabilising a nucleus against particle decay. Nucleonic pairing is also important for the structure of neutron star crust. Studies of nuclei far from stability offer new opportunities to study pairing. Examples include: very neutron-rich nuclei, where di-neutron pairs are believed to be localized in the neutron skin region and heavier nuclei with similar neutron and proton numbers, where deuteron-like proton-neutron pairs with nonzero angular momentum, are expected. The latter, currently unobserved correlations, are expected to have significant impact on nuclear binding in nuclei with approximately equal numbers of protons and neutrons ($N \sim Z$ nuclei), influence isospin symmetry and beta decay, and modify the equation of state of diluted symmetric nuclear matter. Pairing can be probed with a variety of nuclear reactions that add or subtract pairs of nucleons. These reactions can be studied in inverse kinematics at ISOL facilities, such as HIE-ISOLDE or SPIRAL2, with a variety of exotic nuclear beams with modest intensities ($> 10^3/s$).

Drip line nuclei often exhibit exotic decay modes, for example, the proton rich nucleus iron-45 decays by beta emission or by ejecting two protons from its ground state. As the drip lines are approached, the coupling between different nuclear states, via a continuum of unbound states, becomes increasingly more important and eventually plays a dominant role in determining structure in these so called “open” quantum systems. Many aspects of nuclei at the limits of the nuclear landscape are generic and are currently explored in other open systems such as molecules in strong external fields, quantum dots and wires and other solid-state microdevices, crystals in laser fields, and microwave cavities. Radioactive nuclear beam experimentation will answer questions relevant to all open quantum systems: What are their properties around the lowest energies where the reactions become energetically allowed (reaction thresholds)? What is the origin of states in nuclei, which resemble groupings of nucleons into well-defined clusters, especially those of astrophysical importance? What are the most important steps in developing the theory that will treat nuclear structure and reactions consistently?

One of the greatest frontiers for the subject is the synthesis of new elements – adding to the period table; aka nuclear alchemy. This is one of the most challenging endeavours as the probability that a given beam-target interaction results in the synthesis of the new element is almost vanishingly small. Correspondingly, the technology required is at the cutting edge. The beam intensities required are capable of melting the targets and hence targets must rotate to effectively increase their area. Experiments must run for months on end to synthesise a handful of atoms. Nevertheless, and perhaps remarkably, it is possible to determine their chemical properties. This reveals that many of these heaviest elements have a chemistry which is uncharacteristic of their location in the periodic table, for example element 114 (Flerovium)

unpredictably behaves as a noble gas – due to relativistic effects. The most recent advances have been made through the use of a radioactive berkelium-249 target synthesised in a reactor at Oak Ridge, USA, and then transported to Dubna, Russia, to create element 117. Understanding the synthesis limit at which the heaviest element has a significant half-life requires a determination of the shell structure – shell structure provides enhanced stability compared with neighbouring nuclei. Mapping out the single-particle structure in turn crystallises the magic numbers. The UK has played a key role in this endeavour.

The above are just a few examples of how the picture of strongly interacting matter is being pieced together – the scientific vision of the UK community and the ability to play a leading role in equipment develop are key ingredients required for the UK to continue to be at the forefront of discoveries.

10.2 UK Astrophysics programme

What are the Origins of the Elements?

- How, and where, were the heavy elements synthesised?
- What are the key reaction processes that drive explosive astrophysical events such as supernovae, and X-ray bursts?
- What is the equation-of-state of compact matter in neutron stars?
- What are the nuclear processes, and main astrophysical sites, that produce the γ -ray emitting radionuclides observed in our galaxy?
- How do nuclear reactions influence the evolution of massive stars, and how do they contribute to observed elemental abundances?

Nuclear astrophysics is an interdisciplinary endeavour involving nuclear physics measurements and theory, astrophysical modelling and astronomical observations. Through these we seek to understand the energy generation in astrophysical sites and the resultant chemical enrichment of the Universe.

The recent launching and commissioning of a new generation of satellites capable of detecting the x-ray and gamma-ray emissions from the unstable nuclei produced in stellar sites has opened a new observational window. A major challenge is now to reduce the impact of nuclear physics uncertainties in the astrophysical models so that progress can be made in understanding the underlying hydrodynamic development and the impact of rotation and mixing. Probing the key nuclear reactions requires access to both stable and radioactive beam facilities and to complex experimental equipment. The UK programme exploits facilities in Europe, North America and Japan and new programmes are being developed for the major upgrades in progress at HIE-ISOLDE and the ISAC facility at TRIUMF, as well as the next generation facilities at SPIRAL-2 and FAIR which will come on-line towards the end of the decade.

A major theme of modern nuclear astrophysics is the intimate link between the reactions and structure of unstable nuclei, and explosive astrophysical events in the Cosmos as these are responsible for the origins of at least half of the elements heavier than iron. The origin of these elements has already been highlighted as a key challenge. Over half are thought to be produced by the astrophysical r-process which involves a rapid series of neutron-captures, driving far away from the line of stability, followed by their subsequent β -decay. Modern telescope observations of metal-poor stars are revealing relatively robust r-process signatures of elemental abundances, but the astrophysical origin of this process remains a mystery with possible sites being supernovae and merging neutron stars. In order to understand the

conditions of temperature, and neutron density, for the r-process it is absolutely essential to measure the properties of hitherto inaccessible very-neutron-rich nuclei. Theoretical predictions suggest a quenching of nuclear shell structure in these regions that could profoundly influence the path of the r-process. Precision measurements of the evolution of nuclear shell structures of the ground and excited states of highly neutron-rich nuclei will be performed using transfer reactions on the storage ring at the HIE ISOLDE accelerator, CERN. At the FAIR facility, ground-state properties such as mass and half-lives will be measured for whole swathes of nuclei lying along the r-process path.

Amongst the heavy elements there are isotopes known as p-nuclei. These are proton-rich nuclei thought to be produced by multiple photodisintegration reactions in core collapse supernovae. Certain p-nuclei are found to have an anomalously large abundance and their origin remains a mystery. Very little is known of the nuclear reactions in the p-process, and none at all for reactions involving radioactive species. Such measurements will become possible with the storage ring facility at HIE-ISOLDE where the ions can be injected at the (low) energy relevant for astrophysical burning conditions. Complementary experimental developments are underway at the TRIUMF laboratory.

The s-process is thought to produce the remaining heavy elements during hydrostatic burning stages in AGB and massive stars. Here the neutron capture rate is low and the nuclear pathway closely follows the line of stability. One of the remaining challenges is the determination of the nuclear reactions affecting the neutron flux available for the s-process. Alpha-induced reactions on light nuclei are crucial for the production of neutrons while selected isotopes act as poisons, removing neutrons. UK nuclear astrophysicists and astrophysical modellers are collaborating to identify and determine the important reactions, rates and impacts.

Astrophysical X-ray bursts, now being measured extensively in satellite telescope missions such as Chandra, are thought to be generated by thermonuclear explosions in the atmospheres of neutron stars in close binary systems. The enormous spikes in X-ray emission are triggered by a few key reactions of unstable nuclei occurring via isolated resonances. These reactions allow the flow of material from the hot CNO cycles into the region of the astrophysical rp-process (rapid proton capture), with the processing of material possibly extending as far as the region around doubly-magic ^{100}Sn . Direct measurements of the key triggering reactions in the energy region of astrophysical interest require intense low energy radioactive beams from new generation ISOL radioactive beam facilities. The UK has a very active programme at the TRIUMF laboratory, using several leading instruments developed using STFC funding which have a unique capability to address this pressing science question. For the many cases where direct measurements are not feasible due to the low cross-sections, precision indirect measurements must be performed using, for example, transfer reactions to populate key astrophysical resonances. These measurements require access to specialist beams available at a number of the "Large Scale Infrastructures" in Europe, which are supported through past and present EU Integrated Initiatives funds (e.g. JYFL, Orsay, GANIL). In the future the proposed storage ring facility at HIE-ISOLDE offers further exciting opportunities.

The observation of γ -ray emission lines from radioisotopes (e.g. ^{26}Al , ^{44}Ti , ^{60}Fe) shows that nucleosynthesis is ongoing in the cosmos. Determining the astrophysical origins of these lines and utilising the information they potentially provide us on the nature of stellar explosions, e.g. novae and supernovae, is a major

challenge for nuclear astrophysics. A few key reaction rates involving radioactive nuclei need to be determined in order to estimate γ -ray fluxes from potential stellar sites. Measurements of these reactions, which are generally dominated by the location and properties of resonances in the compound system, require intense, high-quality radioactive beams from ISOL facilities, as well as complementary stable beam measurements. Again, the UK has an active and exciting programme in this area at a many international facilities, including TRIUMF, TAMU, ISOLDE, Orsay, Munich, and in the future the storage ring facility at HIE ISOLDE, which will also permit the study of reactions involving isomeric radioactive beams.

The equation-of-state of nuclear matter and the structure of matter of neutron stars are directly linked. A key issue is how the nuclear equation of state evolves as a function of isospin (neutron-proton number asymmetry). At FAIR, within the R3B collaboration, high energy beams of unstable nuclei will be used to induce reactions with beams across a wide range of isospin. For example, first measurements will be performed on the excitation energy of the giant monopole resonance (the collective breathing mode of the nucleus) – this information, reflecting the nuclear compressibility, is vital to predict and understand the structure of matter in the surface region of neutron stars.

The study of nuclear reactions affecting the evolution of massive stars, and the relative abundances of key isotopes such as ^{12}C and ^{16}O , vital for life, represents the low energy frontier of nuclear astrophysics. Here the challenge is to make direct measurements of key reactions, e.g. $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$, $^{12}\text{C}(^{12}\text{C},p)$ and $^{12}\text{C}(^{12}\text{C},\alpha)$, in the low energy/temperature Gamow window in which burning takes place driving slowly evolving quiescent stars. The fusion cross-sections are extremely low and ultimately background from cosmic rays prevents access into this energy regime. At present UK scientists are contributing to the measurements of key reaction cross sections within the LUNA collaboration. The collaboration is actively pursuing an upgrade of the existing facility by acquiring a MV accelerator (LUNA MV project) that will allow for the measurement of the key reactions mentioned above.

10.3 Hadronic Physics research

How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?

- What is the mechanism for confining quarks and gluons in strongly interacting particles (hadrons)?
- What is the structure of the proton and neutron and how do hadrons get their mass and spin?
- Can we understand the excitation spectra of hadrons from the quark-quark interaction?
- Do exotic hadrons (multi-quark states, hybrid mesons and glueballs) exist?
- What are the phases of strongly interacting matter and what is the nature of the quark-gluon plasma?
- How do nuclear forces arise from QCD?

Hadron physics studies the properties of Baryons and Mesons, composite particles comprised of quarks and anti-quarks bound by the strong interaction. The currently accepted theory of the strong interaction is Quantum Chromodynamics (QCD) where the force is thought to be mediated by an exchange of gluons, carrying and coupling to colour charges. A central hypothesis of QCD is that no free colour charges are observed and hence quarks and gluons will not exist as free particles. They will very quickly form bound states, the aforementioned Baryons consisting of three quarks or three anti-quarks and Mesons,

consisting of a quark-anti-quark pair. Different states are allowed by QCD, but experimental evidence for their existence is scarce.

The QCD Lagrangian has yet to be solved from fundamental principles. Theoretical prediction either uses numerical techniques (Lattice QCD) or effective models maintaining the fundamental symmetries of the underlying theory (Chiral perturbation theory, soliton models, Skyrme models, the constituent quark model). All theoretical approaches provide model descriptions of a range of phenomena, but fall short in others. Experimental input and experimental testing is thus crucial for progress in our understanding of these most fundamental composite systems in nature.

This is reflected in the questions raised and pursued by the UK hadron physics community, concentrated in experimental groups at the Universities of Edinburgh and Glasgow and theoretical work done at the University of Manchester. The underlying question of hadron physics is one of emergent phenomena, studying complexity originating from simple rules and a few constituents. These emergent phenomena are reflected in basic properties like the radius (still subject of a recent Nature title page), charge distribution, magnetic moments and mass. Most of the latter is being dynamically generated by the strong interaction and constitutes nearly all the visible mass of the universe.

The experimental study of strongly bound systems falls into two complementary approaches, scattering and spectroscopy. In scattering experiments, the aim is to form an image or measurement of the object under study. In hadron physics, scattering experiments measure form factors, being related to the radius and shape of the nucleon, the underlying distribution of charge and at sufficient energy and resolution the quark distributions inside the nucleon. Moving from inclusive scattering to a detailed reconstruction of the full final state (semi-inclusive and exclusive measurements), more and intricate details are revealed, leading to the recent field of hadron tomography which aims at a complete phase space picture of the nucleon.

Spectroscopy experiments reveal information on a bound system by studying its excitation spectrum. Again, this requires choosing a suitable probe for the excitation and a (nearly) complete reconstruction of the final state. Spectroscopic measurements will yield baryon and meson resonances and help to pin down the quantum number of the ground and all excited states. In that, the valence quarks, relevant degrees of freedom and information on the potential can be measured and compared to model predictions. Indeed, the discovery of new states for conventional and exotic hadrons follows this recipe.

Both experimental approaches can use either electromagnetic or hadronic probes in the entrance channel. Nowadays, the probe chosen is tailored to the quantum numbers to be studied. Electromagnetic probes (beams of photons and charged leptons) define the quantum numbers in the initial state very precisely, while hadronic beams yield a higher cross section for the price of less experimental control.

The UK hadron physics community specialises in the use of photon and electron beam for scattering and excitation experiments. The groups at the Universities of Edinburgh and Glasgow are leading experiments at DESY (HERMES, OLYMPUS), Jefferson Laboratory (Hall A, CLAS, CLAS12, Hall C and GlueX), MAMI (A1 and A2) and MAXlab (in alphabetical order). The experiments are complementary in beam energy, photon and electron probes, kinematical coverage and detection capabilities for the final states. Additionally, there is interest in exploiting the spectroscopic possibilities opened up by the high precision anti-proton

beam at the PANDA experiment at FAIR. In future, experiments at an electron-ion collider are planned to continue the measurements and deepen our understanding of baryons.

The experimental programme for the coming decade can be classified into three main topics - hadron tomography, complete experiments in baryon spectroscopy and the search for unknown hadronic states.

Hadron tomography comprises investigating the full space-time picture of the partons inside a nucleon and working towards a complete description of the properties of the nucleon in terms of these fundamental constituents. The theoretical framework for this are Generalised Parton Distribution functions (GPDs) and subsets and projections of these (e.g. conventional parton distribution functions, form factors). Experimentally, hard exclusive experiments, i.e. lepton scattering experiments at sufficiently high momentum transfer and energy while reconstructing the complete final state, are the best way to study these functions. Deeply virtual Compton scattering and hard exclusive meson production are the prime tools. The UK has been at the forefront of these measurements worldwide, with leading contributions at HERMES and CLAS for both, dedicated instrumentation and data analysis and interpretation. UK groups are also crucially leading European networks for current and future measurements and analysis of hard exclusive reactions.

A complete understanding of the nucleon in terms of GPDs will require an extensive set of measurements over a wide kinematic range and at very high luminosity to acquire the statistical precision needed. The centre for these measurements will be the upgraded Jefferson Laboratory. UK nuclear physics groups are leading several experimental proposals at CLAS12 and Hall A and are invited to contribute their expertise to the development and construction of new detector components specifically aimed at hard exclusive reactions (e.g. CLAS12 CND, Forward Tagger and RICH). UK nuclear physics group are also invited to participate in the study and development of the physics programme and detectors for the Electron Ion collider, the machine poised to lead the experimental physics programme in hard exclusive reactions and lepton scattering after the current experimental campaign at an upgraded Jefferson Laboratory.

Complete experiments in hadron spectroscopy use a unique property of precision experiments with electromagnetic probes. A detailed analysis of the scattering amplitude reveals that the complete scattering amplitude as a function of energy can be determined by a carefully chosen set of observables (the exact number depending on the final state) involving the polarisation of the incoming beam or the target or by measuring the polarisation of the recoiling hadron. A set of suitable combinations of these polarisation observables will completely and uniquely determine the scattering amplitude. While the experimental approach is in principle known since 40 years, only recent advantages in experimental equipment and method over the last decade allow to pursue these complete measurements. The UK nuclear physics group have a strong track record of these measurements and in providing experimental equipment and expertise, notably on polarised photon beams and recoil polarimetry. UK nuclear physics groups are leading a worldwide effort at Jefferson Laboratory and MAMI to provide a complete set of polarisation observables. While crucial measurements have already been completed, the full set of observables and the full energy range still awaits completion. Measurements at MAMI and Jefferson Laboratory overlap in kinematic range and complement each other by using detector systems optimised for different final states. CLAS(12) is optimised for reconstructing charged particle in the final state, while the Crystal Ball/TAPS set-up at MAMI is optimised to reconstruct multi-photon final states. UK nuclear

physics groups will exploit the rich experimental opportunities at both laboratories in the coming decade, providing a complete measurement of the nucleon's excitation spectrum and reveal whether resonance missing in our current models exist.

The search for new hadronic states is directly coupled, but not limited to the search for missing resonances. Missing resonances are just one of many possible new forms of hadronic matter. Other states not consisting of the conventional three quark or quark-antiquark states have been proposed in the literature, with scarce experimental evidence. Similarly to the two topics previously discussed, high precision experiments in terms of luminosity, preparation and measurement of quantum numbers in the initial and final state and the full reconstruction of the latter are needed to establish the existence or non-existence of these so-called exotic states - from glueballs containing no quarks at all to hybrids, molecules and tetra/penta-quark states. The search for these states is embedded in the current data analysis at CLAS and will be a focus for experiments at the upgraded Jefferson Lab with the CLAS12, especially the forward tagger and RICH upgrades, and GlueX experiments. UK nuclear physics groups are leading parts of the experimental development and are building strength in the necessary data analysis and interpretation skills. In the medium future, this expertise will be used to bear fruit at the PANDA experiment at FAIR. In contrast to the electron and photon beams at Jefferson Lab, PANDA will use a high precision anti-proton beam, accessing different combinations of quantum numbers and allowing for a wider, but less targeted search.