

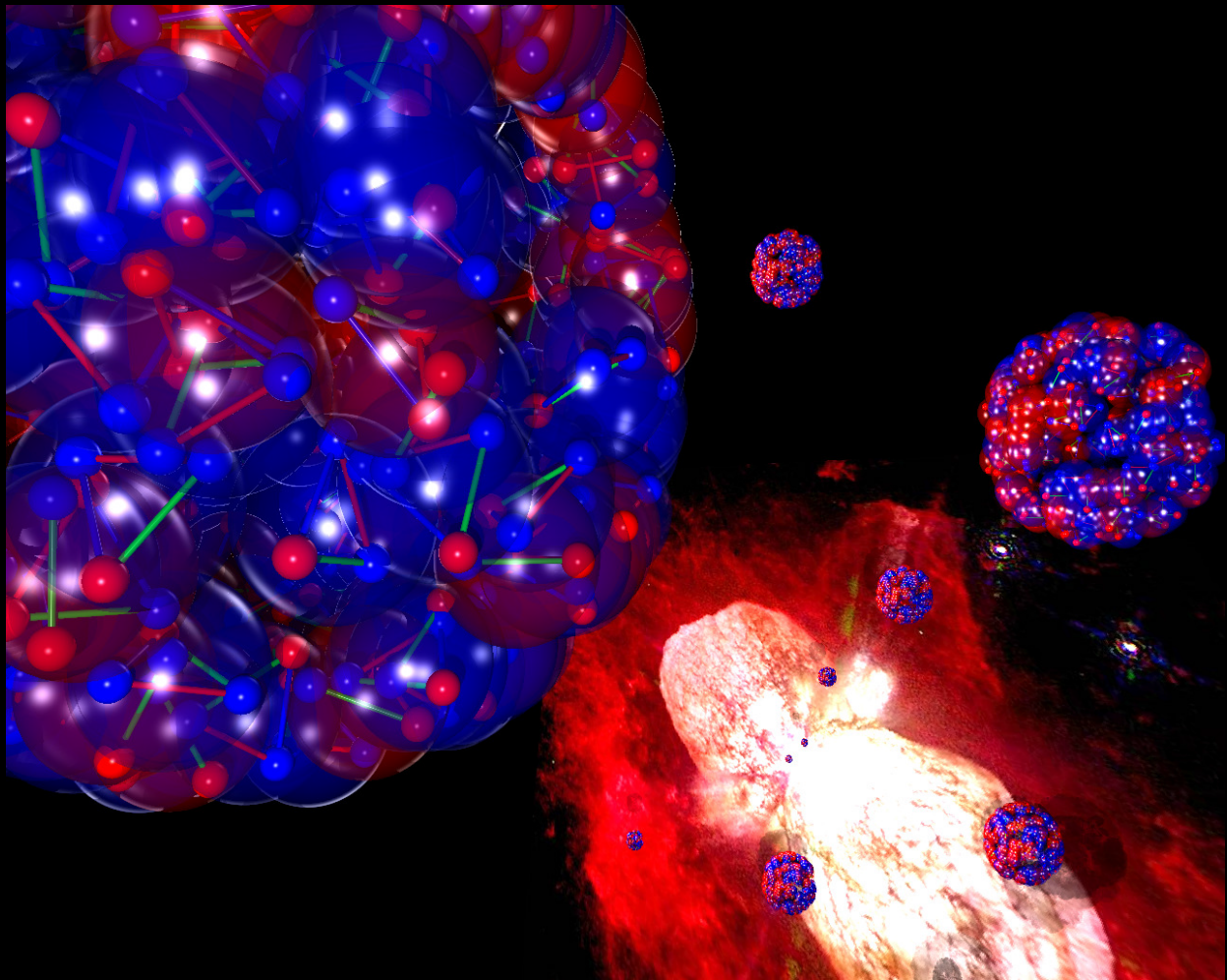
The Physics of Nuclei

Nuclear Matter and

Nucleosynthesis

Report of the Nuclear Physics Advisory Panel

22 April 2016



UK Nuclear Physics Roadmap 2016

Executive summary

The UK Nuclear Physics community has recognised international leadership and expertise and is a growing and vibrant community of 65 academic staff based at 10 institutions. UK Nuclear Physicists are welcomed at international experimental facilities for two primary reasons:

- (1) A leading science programme. This was endorsed in the recent STFC IMPACT report (2015) which ranked our community first in the world by measure of impact and citations.
- (2) Our expertise in the development of state-of-the-art instrumentation. This is vital for the subject to sustain itself and to maintain the viability and credibility of the UK for the future.

There has been significant progress in addressing a number of the science questions outlined in the document, and this science now being pursued by the UK Nuclear Physics community builds on the achievements outlined in the last roadmap document (2012). The focus is on Nuclear Structure, Nuclear Astrophysics and Hadron Physics.

The next ten years in nuclear science will see great advances in our insight into strongly interacting nuclear matter. These include:

- (1) 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.
- (2) The study of key nuclear reactions important for energy generation and nucleosynthesis in a variety of astrophysical sites, from quiescent stars to explosive events (novae, supernovae, and X-ray bursters) and stellar mergers
- (3) The nature of the strong force within hadrons through the characterisation of mesons and baryons, the determination of the quark and gluonic structure of nucleons and the nature of matter an instant after the Big Bang (the Quark Gluon Plasma - QGP)

The UK has scientific leadership in all of these areas.

Some examples of key science highlights since the last Roadmap:

- An unexpectedly large charge radius has been measured in ^{52}Ca , which is not accounted for by state-of-the-art theories of nuclear forces. This observation is difficult to reconcile with recent mass measurements that have pointed towards a double magic nature of ^{52}Ca and opens new questions on the evolution of nuclear size away from stability.
- Coulomb excitation studies of the short-lived isotopes of ^{224}Ra and ^{220}Ra have confirmed experimentally a rigid octupole or pear-shape in ^{224}Ra . These findings contradict predictions made by some mean field theories on the strength of octupole deformation in this region.
- Our understanding of observable signatures of novae nucleosynthesis has advanced significantly, through direct measurements of proton capture on ^{18}F and ^{38}K (radioactive beams) and spectroscopic studies of the level structure in ^{19}Ne and ^{31}S . These studies have reduced the nuclear physics uncertainties in interpreting g-ray observations of novae and in modelling the production of intermediate elements that have been observed in ejecta abundances and pre-solar grains.
- Pion photo- and electro-production measurements have been used to make precise tests of the predictions from chiral effective field theories, which can now be used to describe the pion exchange (“long range”) part of the nucleon-nucleon interaction in nuclei. These measurements also show how well the theories do in explaining phenomena at higher energies, making the link with the regime where perturbative QCD is valid.

Some examples of key technical developments since the last Roadmap:

- The UK NuSTAR project has completed the development of instrumentation for HISPEC/DESPEC and R3B at FAIR. Initial commissioning and exploitation of this instrumentation has commenced.
- Three new project grants have started ISOL-SRS, ALICE-Upgrade and JLab Upgrade. Funding for a Solenoid magnet for ISOL-SRS has been secured following the most recent equipment round. This broadening of support for the wider science programme is welcomed by the Advisory Panel and the community.
- The AGATA spectrometer has been relocated from GSI (Germany) and is now operational at GANIL (France) with an increased number of detectors and improved performance.

UK Nuclear Theory research has been strengthened with STFC support for a University Chair in Nuclear Theory at the University of York with the appointment of Prof. J. Dobaczewski and Dr A. Pastore.

The community has had to manage significant strategic planning issues associated with financial constraints that impacted the outcome of the 2014 consolidated grants round. For example, (1) the reduced 30 month PDRA allocations, and (2) the cross-community and engineering post over commitment following the outcome of project and consolidated grant funding.

Over the next 10 years the community will pursue research programmes at a number of world-leading facilities. The scientific diversity that this offers is essential for the future health of the community and the pursuit of scientific excellence.

Beyond satisfying human curiosity around the workings of nature, pure research in nuclear physics has also tremendous societal impact. The community has an excellent track record in public engagement and outreach in a subject that has a natural fascination for many members of the public.

The Nuclear Physics community continues to have a very productive collaboration with industry. The majority of UK institutions have significant industrial engagement programmes which support knowledge exchange and the development of future REF returnable impact cases.

The involvement in the world-leading FAIR facility remains a high priority for the community and it is believed that there is considerable strategic value in our continued role as an Associate Member in terms of influence over the investment the UK has made in equipment. However, given the extreme financial pressures under which Nuclear Physics operates, with successive cuts to its budget, there is significant concern that the additional 1.7M€ recently requested by FAIR will impact further on the breadth of the community and its research. Hence, the community welcomes the opportunity to ensure our maximum influence through the increased contribution, but **only on the understanding that the FAIR operations and additional construction costs do not impact further on the future project and exploitation funding for the community.**

Recommendations:

- **The UK Nuclear Physics community should be supported to continue to pursue a world-leading experimental and theoretical nuclear physics programme**, focussed on addressing the internationally acknowledged high priority science questions.
- **There must be strong support for physics exploitation at appropriate world-leading facilities.** The declining consolidated grant (CG) financial envelope over the previous two grant rounds has impacted the community. This has resulted in the loss of PDRA's, 30 month PDRA posts and a reduction in the studentship numbers and the investigator time allocation to Universities. While recognising the current financial constraints, **NPAP recommends an increase in support for exploitation in the CG round.**
- **The UK Nuclear Physics community should be supported to continue to exploit its leading position in instrumentation technology in focused areas through continued investment in new projects.** This is essential to the long-term future of the field and provides substantial opportunity for broader societal impact.
- **The UK should support flagship projects in Nuclear and Hadronic physics** including upgrades that capitalise on previous investments and maximise high-quality science output and UK leadership in international projects, with an appropriate uplift in funding to support a balanced programme.
- The funded programme going forward should **support the R&D and design-stage activities that are likely to offer significant future scientific opportunities.**
- **NPAP recommends support for an appropriate portfolio of smaller-scale high-quality projects that capitalise on UK leadership capabilities**, add diversity and novelty, and which provide excellent scientific return for modest investment.
- At the time of the last consolidated grants round by the NPGP in 2014 the major projects ISOL-SRS and ALICE were also in the process of being reviewed. The outcome was that the overall level of effort needed for both the funded consolidated grant themes and the project grants significantly exceeded the amount funded. **NPAP recommends that different STFC panels, such as NPGP, PPRP and the cross community committee, work together in order to ensure that approved projects and science themes are properly funded.**
- **The community and STFC should work together to provide assistance to developing countries using ODA funds.** Establishing a framework for training international research students from ODA countries such as India, China etc could constitute the first step. The UK's international leadership in Nuclear Physics provides a high profile recruitment platform, which will benefit both the UK Nuclear Physics community and the ODA countries.
- **NPAP recommends that cross-disciplinary activities with astrophysicists and astronomers should be facilitated**, for example, by allowing participation in consortium grants without requiring withdrawal from consolidated grants.
- **NPAP recommends STFC continues to support the Postgraduate UK Nuclear Physics Summer School.**

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Nuclear Physics Advisory Panel

Andy Boston (chair)	University of Liverpool
Marialuisa Aliotta	University of Edinburgh
Carlo Barbieri	University of Surrey
Kieran Flanagan	Manchester University
Bjoern Seitz	University of Glasgow
Bob Wadsworth	University of York

1. THE PHYSICS

Overview

Atomic nuclei, consisting of protons and neutrons, make up 99.9% by mass of all visible matter. Despite of being of femtometer scale, they influence matter across 26 orders of magnitude, right up to the largest known stars. The overarching goal of nuclear physics is to develop a detailed and predictive understanding of the fundamental properties of nuclei that can exist in nature and their interactions. Such an understanding requires knowledge of nucleon structure, the nature of the forces between nucleons and the ability to know the limits of existence of bound nuclei. Nucleons interact with each other through the strong interaction which is dominated by complex two- and three-nucleon forces. Additionally, Coulomb repulsion among protons also plays an important role in stability. These forces compete with one another, giving rise to certain configurations of neutrons and protons that are more stable than others. The nuclear landscape spans 118 confirmed chemical elements amounting to thousands of nuclides. However, until very recently, knowledge was limited to the small subset of 254 stable isotopes that are found on Earth. Stable and long-lived nuclei are far outweighed in number by the over 6000 isotopes predicted to exist with very short half-lives (exotic nuclei). Of these more than 3000 nuclides have been synthesized and studied with varying degrees of precision based on production yield, while the other half is ‘terra incognita’. This broad nuclear landscape enables one to isolate or amplify key characteristics associated with a specific physics question and reduce the complexity of the problem.

Protons and neutrons, the nucleons constituting all nuclei, are strongly bound systems of more fundamental particles, the quarks, bound together by gluons, the carriers of the strong force. Different combinations of quarks and anti-quarks can form a large variety of particles, from bound quark-antiquark states (mesons) and three quark states (baryons) to more exotic forms of matter such as hybrid and exotic mesons, the currently discovered heavy tetra- and pentaquark states and recent suggestions of light-quark hexa-quark configurations. With the exception of very high energy density states encountered in ultra-relativistic heavy ion collisions, where the quark-gluon plasma is formed, quarks and anti-quarks are necessarily confined in hadrons. Understanding the complexity and structure of these strongly bound states emerging from few constituents and Quantum ChromoDynamics (QCD) as the underlying quantum field theory is the core of hadron physics research

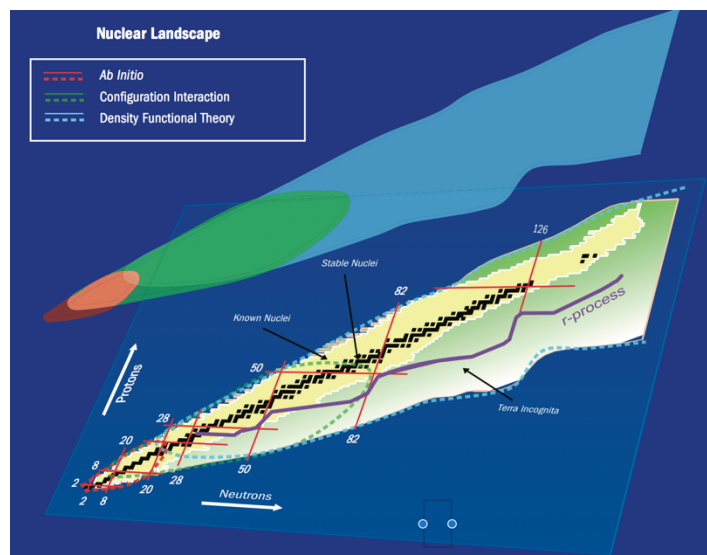


Figure 1: The nuclear landscape showing the strong relationship between experiment and theory

The advent of new facilities and instrumentation has greatly extended the range of precision measurements and, by doing so, is driving the most significant advance in our understanding of the structure of the nucleus in many decades. Critical problems such as the structure of the Hoyle state in ^{12}C and the anomalously long lifetime of ^{14}C are but two examples of questions that are being clarified by radioactive beam facilities. Parallel advances of theoretical understanding of nuclei back these experimental endeavours. Both Structure and Reaction theory is at the base of the analysis and interpretation of measured data. Moreover, highly computational *ab-initio* approaches are now becoming able to link the structure of exotic nuclei and neutron star matter to the underlying QCD.

The UK nuclear physics community has core goals to measure, explain, and use this information for the benefit of the scientific community as well as for wider societal impact. The current research programme aims at developing predictive theories that describe all nuclei and their reactions among

them, which must be grounded in QCD and electroweak theory. Such a complete description is essential to achieve a full understanding of the nuclear processes that power the stars, create the chemical elements, produce solar and supernovae neutrinos, generate cosmic rays and govern their interactions on Earth.

Nuclear physics research seeks to answer fundamental questions about the Universe and our understanding of it:

- What governs the structure and behaviour of atomic nuclei?
- What is the origin of the elements?
- How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?
- What is the nature of nuclear matter?

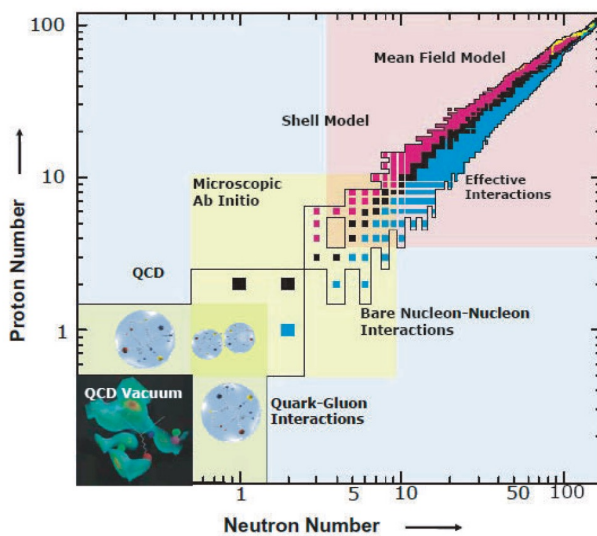


Figure 2: The broad science reach of UK Nuclear Physics

Beyond satisfying human curiosity around the workings of nature, pure research in nuclear physics has also tremendous societal impact. The community has an excellent track record in public engagement and outreach in a subject that has a natural fascination for many members of the public. The UK nuclear physics community is involved in projects associated with future energy production, medicine, radiation and environmental protection, industrial processes and applications, exploration of space, homeland security, technology, and education. Members of the community provide training through institutional MSc programmes and the Nuclear Training education Consortium (NTEC) programme to retain key skills for the nuclear industry.

Despite its relatively small size when compared with European and international standards, the UK community has recognised international leadership and expertise and high quality outputs. This is reflected in the UK nuclear physics programme being ranked first in the world by measure of its impact and citations [2015 STFC IMPACT report]. The UK community is also characterised by its agility and ability to respond to new initiatives. This success has come from a successful strategy of concentrating research on a few key areas where the community can gain leadership and influence.

This Roadmap provides an overview of current experimental and theoretical challenges that underpin research in nuclear physics, and offers a strategic vision to enable the UK community to push the frontiers of knowledge so that it may maintain and enhance the unique and world leading research programme.

1.1 Stable, Unstable and Exotic Nuclei: From the Mystery of Creation to the Limits of Existence

Stable nuclei represent a relatively small subset of all possible configurations of nucleons in nuclei. For most of them, many of their global properties (masses, radii, ground state spin and parities) are known as well as their origin. We know for example that hydrogen, some helium, and traces of other light elements (lithium, beryllium and boron) were all produced soon after the Big Bang, and that most of the elements up to the iron mass region are created in the hot interiors of stars, through well-defined stages of nuclear fuel ‘burning’. For others, work remains to be done to fully describe the complex structure of their spectra (excited states, particle and gamma widths, spins and parities) especially at relatively high

excitation energies. And many open questions remain about the astrophysical processes and sites that lead to their creation.

Unlike stable nuclei, unstable (often exotic) nuclei are less well known. Indeed, some are predicted to exist (according to our understanding of nuclear forces) but have never been created on Earth. Key questions about unstable and exotic nuclei relate both to their *nuclear structure* properties (masses, binding energies, decay half-lives, excited states) as well as to their *nuclear astrophysics* origin in the universe, e.g. during explosive scenarios of stellar evolution where extreme temperatures and densities are possible.

Nuclear physics seeks a quantitative and all-encompassing description of nuclei that is grounded in QCD and electroweak theory. The field is an important part of the study of many-body fermionic systems, the understanding of which remains one of the great challenges of modern science. For nuclear structure and reaction physics this has led to an overarching set of questions, which can be summarised as:

- What determines the limits of nuclear existence and are there new forms of structure and symmetry at the limits of nuclear binding?
- What is the nature of nucleonic matter and its equation-of-state?
- Can nuclei be described in terms of our understanding of the underlying fundamental interactions of the theory of QCD?
- What mechanism drives the emergence of simple patterns in complex nuclei?

The nuclear physics questions that are relevant to astrophysics are:

- What are the nuclear processes that drive explosive events such as novae, supernovae, and X-ray bursts?
- How do nuclear reactions govern quiescent stellar evolution and determine the fate of massive stars?
- What are the nucleosynthesis processes that determine the abundance distributions of elements in the Universe and where do these processes occur?

Much progress has been made in the field since the last report in 2012, however fundamental answers to the above questions demand a significantly enhanced level of understanding of atomic nuclei. This has motivated significant worldwide investment in both the theoretical and experimental aspects of the subject in order to achieve the final goals.

Of the known isotopes, there are small subsets that isolate or amplify key characteristics associated with a specific physics question and reduce the complexity of the problem. State-of-the-art theories predict that many of these will reside far from stability, which in turn is driving the development and construction of the next generation of facilities. Interestingly, most of these exotic nuclides that will aid our understanding of the nuclear force are also believed to play a key role in the synthesis of elements in various astrophysical scenarios.

The limits of nuclear existence are defined at the extremes of proton-neutron ratio, mass, angular momentum and temperature. The limit of proton-neutron ratio is as the point at which the nuclear force will no longer bind a nucleon, which would then literally “drip” out of the nucleus (and hence the name “drip line”). In many heavier systems, the limit is defined as the point at which the nuclear force no longer keeps all nucleons together. In the case of the neutron drip line the limit of existence was thought to be known only up to oxygen, but even here new measurements suggest that ^{26}O could now be reconsidered as a bound system. At the proton-rich limit, the Coulomb barrier can delay proton emission from unbound nuclei, making them accessible experimentally. A reasonable understanding is emerging of the limits of existence for ground states of heavy nuclei, but recent work has pointed to possibilities of longer-lived isomeric states beyond the expected boundaries of the nuclear landscape. At the heaviest elements, it would be expected that fermium with $Z=100$ would be the last bound element against spontaneous fission, but the discovery of elements up to $Z=118$ point towards a region of

stability and long-lived nuclei. This provides more evidence for the compelling need of refining mean-field theories of nuclei by linking them to the *ab-initio* approach to understand the nuclear force.

The UK experimental and theoretical communities have leadership in the study of nuclei towards the drip lines and heavy elements. This is demonstrated through numerous roles as experiment and collaboration spokespersons at world leading facilities, membership of laboratory programme advisory committees as well as acting as scientific conveners for major experimental setups. On the theoretical side the UK's leadership in mean-field, reaction and *ab-initio* approaches to the nuclear many-body problem has led to regular invitations to work with several experimental groups at major facilities around the world.

The **UK experimental Nuclear Structure community** has focused its research on areas where the greatest opportunity for transformational advance exists. Examples of some of the key advances by or in participation with UK scientists include:

- An unexpectedly large charge radius has been measured in ^{52}Ca , which is not accounted for by state-of-the-art theories of nuclear forces. This observation is difficult to reconcile with recent mass measurements that have pointed towards a double magic nature of ^{52}Ca and opens new questions on the evolution of nuclear size away from stability.
- The introduction of novel *ab-initio* methods for calculations has reached open shell isotopes and nuclear masses up to $A\sim 100$. These breakthroughs led to new understanding of the drip line behaviour of O and Ca chains and how it depends on three-nucleon forces based on QCD theory.
- Evidence for a triangular D_{3h} symmetry in ^{12}C has been observed, supporting a triangular cluster model of ^{12}C and potentially forming the basis for more precise models of carbon's structure important for understanding nucleosynthesis in astrophysical environments.
- The production of exotic isotopes in the doubly mid-shell region of the nuclear chart centred around ^{166}Gd and ^{164}Sm and the discovery of new isomeric states has highlighted the presence of complex variations in deformation that may give rise to a deformed $N=100$ shell gap for $Z\leq 66$ which would impact on r-process abundance calculations.
- Coulomb excitation studies of the short-lived isotopes of ^{224}Ra and ^{220}Ra have confirmed experimentally a rigid octupole or pear-shape in ^{224}Ra . These findings contradict predictions made by some mean field theories on the strength of octupole deformation in this region. This work is also important in the experimental searches for electric dipole moments (EDM) in atoms and highlights $^{223,225}\text{Ra}$ as systems with potentially octupole-enhanced EDMs.
- Measurements have been performed on multiparticle isomeric states in proton-unbound nuclei in the mass 150 region. These show a remarkable stability against proton emission given their high excitation energy, which will impact on nuclear existence beyond the drip line.
- The UK has led a series of measurements that has mapped out isospin-breaking interactions in nuclei, examining the subtle difference between the effective pp, nn and np interactions in the nuclear medium. Techniques have been developed for extracting these "isospin-non-conserving" interactions and comparing them with the known properties of the nuclear interaction measured in free space. These fundamental

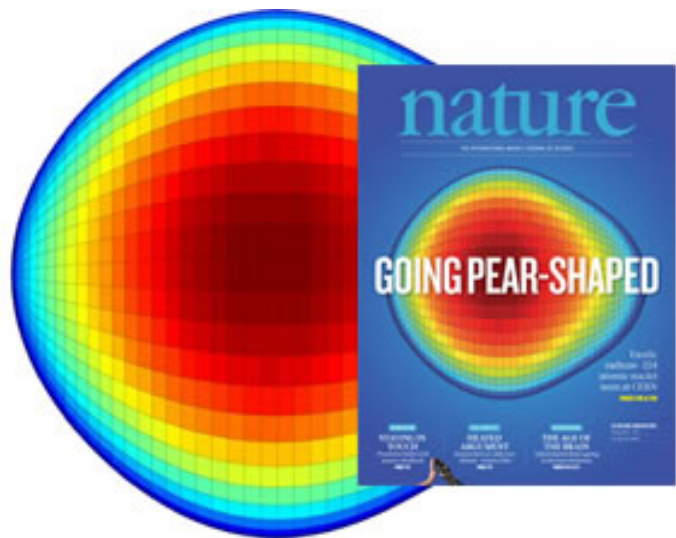


Figure 3: The observation of rigid octupole (pear-shape) in ^{224}Ra

results are yielding important data for nuclear models that attempt to predict the limits of nuclear existence.

- The UK has led a series of measurements to study structure at the limit of angular momentum, close to the fission limit, where novel deformed triaxial structures are found.

Progress in understanding the nuclear quantum system requires that experiment and theory work together harmoniously with new theoretical predictions being tested by experimentalists and unforeseen experimental discoveries pushing theoretical advances. This is highlighted by recent measurements of the neutron-rich calcium isotopes, where new, previously unexpected, shell closures have been observed in the mass 50 isotopes. This has influenced theoretical developments of *ab-initio* methods and theories of three-nucleon forces, which now point to a new location of the neutron drip line at ^{60}Ca , a region which will be accessible for testing at future fragmentation facilities. Such developments indicate the potential for further exciting discoveries of unexpected nuclear behavior in regions far from stability. The investigation of these key nuclei will directly feed into the description of electroweak and QCD interactions that are relevant to other fields (e.g. neutron star cooling, merger events, and even searches for neutrino mass properties).

The **UK experimental Nuclear Astrophysics community** has a focussed portfolio of activities both for quiescent and explosive stellar evolution. Studies of properties and reactions of unstable nuclei are essential for explosive astrophysical scenarios as they influence the path of nucleosynthesis and energy generation in novae, X-ray bursters, and supernovae. Major advances have been achieved for a wide range of explosive H and He burning scenarios, including measurements relevant for cosmic γ -ray emitters (e.g. ^{18}F , ^{26}Al , ^{44}Ti) and for non-solar isotopic abundances in meteorites.

Some key recent highlights from experiments performed at stable- and radioactive-beam facilities are briefly summarised below:

- Improved understanding of the key reactions triggering X-ray bursts through a time reverse measurement using high intensity radioactive beam, and also via a novel beta-delayed proton decay study.
- Our understanding of observable signatures of novae nucleosynthesis has advanced significantly, through direct measurements of proton capture on ^{18}F and ^{38}K (radioactive beams) and spectroscopic studies of the level structure in ^{19}Ne and ^{31}S . These studies have reduced the nuclear physics uncertainties in interpreting γ -ray observations of novae and in modelling the production of intermediate elements that have been observed in ejecta abundances and pre-solar grains.
- The radioisotope ^{26}Al is an important observable in both gamma-ray astronomy and pre-solar grains providing information on massive stars and the early Solar System. Recent experimental measurements have led to reduced uncertainties in the modelling of ^{26}Al production in massive stars and novae.
- Recent observations of ^{44}Ti decay by the NuSTAR (NASA) satellite have demonstrated surprising asymmetry in the distribution of this isotope in core collapse supernovae remnants. The most stringent limits of the destruction rate of this isotope during such an explosive event have been determined by a direct measurement using a ^{44}Ti beam derived from highly irradiated accelerator components.
- Low-energy measurements of proton capture reactions on ^{17}O at Laboratory for Underground Nuclear Astrophysics (LUNA) have led to firmer constraints on nucleosynthesis in novae as well as to a new, improved determination of a key resonance strength with important implications on expected oxygen isotopic ratios from AGB stars and pre-solar grains.
- Neutron capture measurements on radioactive branching point nuclei of the s process provide unique insights into the sites of the astrophysical s-process and the s-process reaction path. For example, first neutron capture measurements on ^{63}Ni at n_TOF/CERN allowed stronger constraints on the Cu yields from explosive nucleosynthesis in the subsequent supernova.

This success has been made possible by a strong UK leadership driving experimental campaigns at a wide range of world leading laboratories, using state of the art equipment and techniques, much of which exploits previous capital investment by the UK. Our access to a range of experimental facilities allows us to be responsive to new opportunities arising from advances in astrophysical observations and modelling.

Yet, many open questions remain. For example, it is not clear why astronomical observations reveal abundances of lithium isotopes many times away from theoretical predictions. These may stem from an inaccurate knowledge of the specific reaction rates involved in their creation and destruction or may indicate problems with the Standard Model of particle physics, thus requiring new physics insights. Similarly, anomalous abundances of some rare isotopes are observed in pre-solar grains and in the composition of novae ejecta. Uncertainties in the carbon fusion processes make it impossible to predict which stars will explode as supernovae. It is not clear how many neutrons can be produced by the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reactions to initiate the slow neutron process. Nor is it clear where the r-process takes place and how to account for the required neutron densities (in excess of 10^{20} n/cm³) necessary to make it possible.

New observations using Gaia, Fermi, NuSTAR, the Very Large Telescope, and other state of the art instrumentation are providing a wealth of information on elemental and isotopic abundances, particularly from early stars (where nuclear processes can be quite different), challenging our understanding of the origin of heavy elements in the universe. 3D hydrodynamic stellar models reveal the strong impact of rotation and mixing on simulations, and so predict new nuclear processes affecting the nucleosynthesis in these stars. Supernova (SN) models do not produce conditions for the r process, and so there is much focus on identifying the possible sites of the r-process. The interpretation of these developments in observations and modelling requires improved nuclear physics input.

Answering these outstanding questions, and providing the needed nuclear physics input, requires accurate measurements of nuclear cross sections directly at the energies of astrophysical interest, as well as major investments at various laboratories for specific and more intense radioactive beams. For heavy element nucleosynthesis, closer ties are needed with the theory community, to provide robust and consistent predictions of the nuclear properties (masses, decay rates, etc) for the regions of the nuclear chart inaccessible to experiments. Networking activities between the disciplines involved in understanding the origin and evolution of the elements (experimental nuclear physics, theoretical nuclear physics, multi-messenger observations, stellar modeling, grain measurements, etc) are vital. Initiatives like the BRIDGCE network provide an important link but more support in enabling such activities is needed.

NPAP recommends that cross-disciplinary activities with astrophysicists and astronomers should be facilitated, for example, by allowing participation in consortium grants without requiring withdrawal from consolidated grants.

1.2 Hadronic Constituents: The Building Blocks of Matter

Hadron physics is concerned with the study of the underlying structure and interactions of nuclear matter at the most fundamental level, that of quarks and gluons. Ultimately, the very existence of nuclei is due to the interactions of colour charged quarks and gluons, which are described by QCD. The key questions that the UK hadron physics community seek to address are:

- What is the structure of the proton and neutron in terms of their most fundamental constituents and how do hadrons get their mass and spin?
- How does subatomic matter organise itself and which phenomena emerge?
- What is the mechanism for confining quarks and gluons in strongly interacting particles?

- What are the phases of strongly interacting matter and what is the nature of the quark-gluon plasma?
- How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?

Nucleons (protons and neutrons) are simply the most common manifestations of the bound states of QCD, but make up almost all of the visible mass of the universe. To study nuclear matter at the fundamental scale requires a probe with a spatial resolution much smaller than the size of the nucleon. However, one of the consequences of QCD is that the picture changes dramatically depending on the scale of resolution: a hadron appears as a bound system of valence quarks (three in a baryon, a quark-anti-quark pair in a meson) when illuminated with a low-energy probe; but as a teeming sea of quarks and gluons when illuminated with a high-energy probe and a whole range of different manifestations in-between.

The properties of hadrons, such as their mass and spin, are a direct consequence of their complicated internal dynamics, which despite dramatic progress in recent decades is still not entirely understood. For example, it is known that the Higgs-generated mass of light quarks is three orders of magnitude smaller than that of the nucleon. How the total mass of the nucleon emerges from the internal dynamics of quark and gluon interactions is still very much an open question. Likewise, how the spin of the nucleon is composed of the spins of its constituents, the so-called “spin puzzle”, is another open question. We know that only a third of the nucleon spin is contributed by the intrinsic spin of quarks, but precise measurements of the effect of gluon spin and of the orbital motion of both quarks and gluons which have to contribute the remaining fractions await the results of experiments that are only now becoming possible.

The challenge of describing nuclear matter at the fundamental scale presents itself because the strength of the interaction is strongly scale dependent. Precision tests of QCD are possible only in the hard scattering limit, corresponding to very short distances, much smaller than the size of nucleons and nuclei. On the scale of nucleons, the strength of the interaction increases dramatically as quarks are separated, resulting in the phenomenon of confinement. Consequently, there is no analytic solution to the QCD Lagrangian in the energy regime relevant for normal nuclear matter and effective theories, such as chiral perturbation theory, must be used to infer the properties of the underlying fundamental theory. In recent years, numerical QCD calculations formulated on a discrete space-time lattice have begun to make significant progress, allowing predictions to be made of the properties of some light nuclei. Nevertheless, the field remains largely phenomenological and theoretical advances require guidance from experiments performed across the widest possible range of energy (distance) scales on a wide range of nuclei using a variety of experimental probes.

The tools of choice, for precision studies of the bound states of QCD, are photon and electron beams. There are a number of ways a hadron can be studied in such an experiment. It can be gently “nudged” to excite it into a resonant state, the decay of which provides information about the short-lived particle revealing its internal structure and allowed transitions. This is the field of hadron spectroscopy, which also seeks to discover evidence for new “exotic” particles, for example gluon-only resonances or bound states of more than three quarks. These are allowed by QCD but experimental hints have only appeared recently. Understanding the existence (or absence) of these states presents another way to explore the dynamics of the strong interaction. Hadron resonances are studied by UK nuclear physicists in fixed targets at Jefferson Laboratory (Lab) in the US (CLAS and GlueX collaborations) and at the Mainz Microtron (MAMI) in Germany.

The nucleon can also be probed in elastic collisions, where electrons are scattered from the charge distributions inside it. This yields information about the size and shape of the nucleon and the quark density, illuminating the differences between protons and neutrons. Recent highlights of this programme revealed the importance of two-photon exchanges in the electron-nucleon interaction, which challenges the accepted picture of charge distribution within the nucleon.

Using electron beams at higher energies, it is possible to transfer so much momentum to the target nucleon that other particles are “knocked” out of it—for example mesons or high-energy photons from an intact nucleon — or the target particle may fragment into a number of newly formed hadrons. This is a form of tomography: the scattering in these interactions happens directly from the quarks inside the nucleon and tells us about its internal dynamics and quark distributions, building up a 3D moving picture of nucleon structure. A vibrant experimental programme is underway in the CLAS, Hall A and Hall C collaborations at JLab, which has just doubled its maximum electron beam energy to 12 GeV. This is opening up a region of phase space that has not been accessed before and will lead experimental development of the field at the intensity frontier. With a mixture of precision measurements and observations of extremely rare processes, the JLab programme will address such questions as the generation of hadron mass, the composition of nucleon spin, quark distributions, spectroscopy of mesons and baryons and the search for exotic states.

Since the last NPAP roadmap, the **UK Hadron Physics community** has been at the forefront of a number of important advances in this research area. This work has exploited two complementary approaches used to explore the properties of nuclear matter at its fundamental scale.

Selected highlights from the electron beam experiments at MAMI and JLab are:

- Pion photo- and electro-production measurements have been used to make precise tests of the predictions from chiral effective field theories, which can now be used to describe the pion exchange (“long range”) part of the nucleon-nucleon interaction in nuclei. These measurements also show how well the theories do in explaining phenomena at higher energies, making the link with the regime where perturbative QCD is valid.
- Measurements of exclusive and semi-exclusive reactions, combined with significant theoretical developments in Lattice QCD and Dyson-Schwinger Equation approaches, have given insight to how the properties of nucleons emerge from the non-perturbative nature of QCD.
- Recent developments in beam, target and recoil polarisation have started to bear fruit in the measurement of observables that can provide much more information than cross sections for both the spectra of hadrons and studies of nucleon structure. In particular they have provided confirmation of several new states in the Particle Data Group’s Baryon table.
- Studies of the subtle effect of two-photon exchange in electron scattering have begun to resolve discrepancies between form factor measurements that were obtained using two different experimental techniques (Rosenbluth separation and recoil polarisation).
- Links to other areas of nuclear physics have been addressed as well, such as a new measurement of the neutron skin thickness by coherent pion photoproduction, which is intimately linked to descriptions of the nuclear equation of state and has important consequences for models of neutron stars.
- The correlations among nucleons and nuclei have been shown to be predominantly between protons and neutrons, which gives rise to a surprising consequence that protons, as the minority particle species, have a higher average momentum in nuclei than neutrons.

The excitation spectrum of light and heavy quark mesons has become a comparatively recent focus within the UK hadron physics electron beam community, with most of the effort concentrated at experiments at JLab (CLAS at Hall B with 6 GeV and 11 GeV beams, GlueX in Hall D with 12 GeV beams). Meson properties have also been studied at HERMES, DESY, Hamburg, Germany and MAMI, Mainz, Germany.

An alternative way to test the properties of QCD matter at its fundamental scale is in the high temperature and high-density environment of ultra-relativistic heavy-ion collisions. The UK has a prominent role in ALICE, an experiment optimised to study high-energy, heavy-ion collisions at the CERN Large Hadron Collider. Nuclear collisions at these extremely high energies create conditions similar to those a few microseconds after the Big Bang, before protons and neutrons first formed, when all

strongly interacting matter was a plasma of quarks and gluons. As a consequence of asymptotic freedom, QCD simplifies at high energy and the expectation was that the quark-gluon plasma would behave much like an ideal gas. However, it is not only the weakening of the interaction at high energy that drives the transition from hadrons to quasi-free quarks and gluons, but also charge screening effects in the high density medium. As a consequence, the quark-gluon plasma is a richly complex new phase of matter that exhibits remarkable collective properties, such as near perfect fluidity. Ultra-relativistic heavy-ion collisions provide a unique environment for exploring the structure and thermodynamic properties of QCD at high energy and the nature of confinement. More generally, they can provide new insight into the properties of strongly interacting matter not accessible in other ways. For example, a recent measurement of the mass difference of light nuclei and anti-nuclei by ALICE, exploring possible subtle differences in the ways that protons and neutrons and their corresponding antiparticles bind together, has provided the most precise test of Charge, Parity and Time Reversal (CPT) symmetry in the strong interaction to-date. Furthermore, ultra-peripheral heavy-ion collisions have been shown to provide a new way to probe the gluon density in nuclei at high energy. The study of strongly interacting matter in ultra-relativistic heavy-ion collisions therefore provides complementary information to that obtained from electron-nucleon and electron-nucleus collisions on the structure of strongly interacting matter at the fundamental scale of quarks and gluons.

The ALICE experiment has produced a rich programme of physics since the LHC started. The UK has played a full and leading role in this physics programme. Some physics highlights coming from the UK's contribution to ALICE are:

- Studies of strange particle production have shown that the relative production of baryons and mesons is momentum dependent. At low momentum the ratio is determined by hydrodynamic flow, while at high momentum it is determined by fragmentation. Between these two limits, the ratio was found to be sensitive to the interplay between hydrodynamical expansion and the coalescence of constituent quarks, providing insight into the mechanism of confinement.
- In heavy-ion collisions, the production of multi-strange ($S=2$) baryons is driven by gluon fusion in the quark-gluon plasma phase, leading to enhancement. Comparing strange particle production in pp, p-Pb and Pb-Pb collisions showed that the enhancement evolves smoothly from pp to p-Pb, hinting at possible quark-gluon plasma formation in small systems at LHC energies.
- Ultra-peripheral heavy-ion collisions explore particle production in a regime where the beam-beam interaction is mediated by an electromagnetic probe. At LHC energies they provide access to the gluon density distribution in nucleons and its modification in nuclear matter. Measurements of forward and centrally produced vector mesons have helped to constrain the theoretically uncertain nuclear gluon density, and hence improve the description of the initial state in Pb-Pb collisions.
- Studies of jet production provide a direct connection to quark and gluon scattering in the initial stages of high-energy nuclear collisions. The survival of jets is predicated on their interactions with the surrounding medium providing insight into the dynamical properties of the quark-gluon plasma in central heavy-ion collisions. On-going work into the distributions of particles within jets promises to shed light on the energy loss mechanisms at play in the quark-gluon plasma.
- Heavy flavour quarks (charm and bottom) provide unique insight into thermal history of the quark-gluon plasma and the interplay between radiative and collisional processes. The production of the charmed lambda baryon has been used as a benchmark study for the upgrade of the inner tracking system in ALICE. Because of its short decay length (60 microns) and small branching ratio into an all-charged particles final state (5%), separating its decay vertex from the primary interaction vertex places strong constraints on the precision with which tracking must be performed.

1.3 Theoretical Nuclear Physics

Theory plays a fundamental role in investigating the structure of hadronic systems and in supporting current experimental studies. While high precision data are becoming available, the use of hadronic probes gives rise to a multitude of reaction mechanisms and final state effects that must be under

control in order to disentangle information on the structure of nuclei. Very important aspects include the break-up of Borromean isotopes as well as transfer and high-energy knock out reactions; on which the UK has a long standing high reputation.

Ab-initio theories aim at predicting the structure of nuclei from first principles, testing this predictive power against experiment is fundamental to improving our knowledge of the strong nuclear force. This in turn has implications on constraining calculations of nucleonic and neutron star matter. For heavier nuclei, mean-field approaches based on nuclear density functional theory (DFT) are the only sensible way to analyse deformation, isotopes along the nucleosynthesis path and fusion reactions

The UK nuclear physics theory community performs high quality research that covers a broad spectrum of topics. These range from hadron structure (and links to the underlying theory of QCD) to the complexity of nuclear reactions. Effective Field Theories (EFTs) are used to investigate phenomena in few-body systems and the proton radius puzzle. New advances are being brought to reaction theory, especially for high-energy knockout and for transfer reactions where the UK has a long-standing international reputation. In addition, the community has focused on implementing new *ab-initio* techniques to describe nuclear structure. EFTs are exploited to unpick the role of three-body forces and feed directly into the UK research in *ab-initio* nuclear structure that aims at answering fundamental questions on the structure of exotic drip-line isotopes, and all the way to neutron star matter. The recent addition of a new group in York has strongly boosted the research programme in nuclear mean-field/density functional theory (DFT) and fusion in heavy nuclei. Overall, the variety of research interests is rather healthy and is the basis for a strong future growth. Most of these efforts benefit from novel ideas and from advances of high performance computing. Remarkably, the UK scientists have produced a number of public numerical codes for both reaction theory, nuclear DFT and *ab-initio* calculations. Many of these are in use for analysing experiments.

In collaboration with researchers in the US a systematic study of Compton scattering from the proton and deuteron in the framework of heavy baryon chiral effective field theory. For the proton a high-quality description of world data has been obtained up to 350 MeV, leading to an unprecedented accuracy in the extraction of the electric and magnetic polarisabilities. Comparison to data from MAX-lab allowed new constraints on the polarisabilities of the neutron and improved the values reported by the Particle Data Group (PDG). This is important in testing our knowledge of the interaction between the electroweak and the strong nuclear force. Moreover, the magnetic polarisability is also a crucial constraint of the Lamb shift in muonic hydrogen, the least-known ingredient of the “proton-radius puzzle”.

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. In particular, the theory of (d,p) reactions has advanced in new directions by combining both deuteron breakup and non-locality of optical potentials, clarifying how the latter should be used in the case when they are explicitly energy-dependent. This opens the way for linking state-of-the-art *ab-initio* approaches that can provide nucleon-target optical potentials with nuclear reaction theories.

Ab-initio nuclear structure calculations aim at achieving predictive power at the limits of stability. Recent first principle calculations have reached atomic masses of $A \sim 100$ and above. Coupled cluster and many-body Green's function theories have been developed and as part of an international collaboration these methods have been extended to truly open-shell isotopes and studies of full isotopic chains.

The Green's function formalism has been extended to include 3-nucleon interactions. At the infinite matter level, this has provided an improved saturation point and a better description of neutron-star observables. Green's functions techniques have also been used to characterize quantitatively the isospin asymmetry dependence of high-momentum components, and the implications for the symmetry energy.

Several aspects of nuclear DFT are now being investigated in the UK. The appointments at York have a long history of leadership in the advance of EDFs and several computer codes for structure calculations have been published that are widely used by physicists worldwide. A very recent advance is the use of effective theory principles to devise nonlocal functionals. 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 EDFs are exploited in time dependent Hartree-Fock (TDHF) calculations within the UK. Very importantly, the recent studies of nuclear fission are now reproducing the experimental distribution of mass fragments of ^{240}Pu . These have opened the way to more sophisticated time-dependent calculations, now being attempted by other international groups.

Recommendation: The UK Nuclear Physics community should be supported to continue to pursue a world-leading experimental and theoretical nuclear physics programme, focussed on addressing the internationally acknowledged high priority science questions.

2. THE FACILITIES

Nuclear Structure Physics and Nuclear Astrophysics

Broadly speaking, experimental studies take place at particle accelerators capable of delivering stable or unstable (often exotic) nuclei with a wide range of energies and intensities. Which facility is best suited to a specific study, depends on the physics process under investigation and the experimental technique used to probe it. Both the Nuclear Structure and Nuclear Astrophysics communities study nuclei at the extremes. This requires the exploitation of the best currently available:

- Stable beam facilities, such as GANIL, Jyväskylä and Argonne National laboratory (ANL)
- Fragmentation facilities, such as those at GSI, GANIL, RIKEN in Japan, NSCL at Michigan State University
- ISOL facilities, such as ISOLDE at CERN and ISAC at TRIUMF

ISOL facilities provide unique access for precision measurements on nuclei away from stability, whereas fragmentation facilities enable the boundaries of known nuclei to be extensively probed. A key UK contribution to the global effort has been to lead the development of experimental equipment to select very rare events at these and future facilities such as FAIR. An example of this has been the detectors for HISPEC, DESPEC and R3B experiments (part of NuSTAR project at FAIR). Some of which have already been exploited at RIKEN and other laboratories.

Members of the UK community currently lead science programmes at Argonne National Laboratory in the US, the University of Jyväskylä (Finland) and at fragmentation facilities such as RIBF-RIKEN (Japan) and NSCL (US). For example, the Gammasphere spectrometer at ANL and the JUROGAM spectrometer at Jyväskylä have pushed the limits of nuclear properties through gamma-ray spectroscopy. At RIKEN studies of the trans-actinide elements, isomer experiments and many nuclear spectroscopy experiments have been performed, the latter with the EURECA setup. Equipment designed and constructed for the NuSTAR project at FAIR (such as AIDA and FATIMA) is being commissioned and exploited in these programmes prior to use at FAIR. In order for the UK community to effectively exploit the future FAIR facility to its full potential it is essential that it has access to current world-leading facilities and continues to develop new instrumentation to be used in these facilities in preparation for the next generation of experiments at FAIR.

A major upgrade of the GANIL facility (SPIRAL 2) is currently underway, in 2014 the AGATA spectrometer was moved to GANIL to exploit the existing high intensity stable beams. AGATA together with the VAMOS magnetic spectrometer and other key ancillary devices is a key part of an extended campaign of experiments with significant UK scientific leadership. In 2015 the first phase of the HIE-ISOLDE facility was completed and radioactive zinc beams were delivered at 5 MeV/u to the MINIBALL experiment. The upgrade to 10 MeV/u beams is expected in 2018. The ongoing programme of investment into ISOLDE will enable many new and detailed precision measurements of unstable nuclei. The latest project grant

(ISOL-SRS) for this facility is therefore welcomed by the community. Measurements such as masses and radii of nuclei, decay studies of proton-rich nuclei and detailed spectroscopy performed via Coulomb excitation will be possible over the next 10 years.

The delayed start of FAIR resulted in an international review of the project in spring 2015. This led to a re-evaluation based on a Modularised Start Version (MSV) with science questions that will be open and exciting in 2025. As a result of this, the physics programmes associated with NuSTAR and APPA (Atomic, Plasma Physics and Applications) were viewed as the top priorities by the international review panel. The science areas in which the UK community has direct involvement at FAIR (NuSTAR) are rated with the highest priority. It is envisaged that prior to the completion of FAIR experiments will be performed at the existing GSI facility. These will profit from the upgraded accelerator system and the equipment developed for the NuSTAR project, and will start in 2018.

Nuclear astrophysics research poses reaction-specific challenges and requires not only appropriate facilities but also ad-hoc experimental approaches. For example, non-explosive stellar evolution and nucleosynthesis are governed by reactions involving stable nuclei. Although these nuclei are readily available on Earth, reaction cross-sections at sub-Coulomb energies (those of astrophysical relevance) are painstakingly difficult to measure. This translates into the need for time-extensive experiments and thus for dedicated facilities, ideally underground where the cosmic-induced background is greatly suppressed, such as LUNA (Italy).

By contrast, the processes that power astrophysical explosions such as novae, supernovae, X-ray bursts, typically involve highly exotic nuclei, which do not normally exist on Earth because of their short half-lives. Thus, such nuclei must first be produced in the lab before an attempt at studying their properties or indeed their interaction with other nuclei. Such an approach requires a range of low energy facilities such as ISAC at TRIUMF (Canada).

The UK Nuclear Astrophysics community leads experiments at international facilities including TRIUMF, ANL, MSU, GANIL, CERN, to name a few. Activities in experimental nuclear astrophysics have matched, and exploited, the large investments in satellite missions of the last decade, which in turn provided a wealth of astronomical observables against which models of stellar evolution and nucleosynthesis can be tested. Now major investments at various laboratories for specific radioactive beams are needed for the next advances and the UK community needs to be able to respond quickly as these become available over the next few years.

Hadron Physics

The main facility for studying the nucleon is a high-intensity polarised electron accelerator coupled with a high resolution and/or large acceptance detector systems, offering a unique control over all relevant degrees of freedom and a precise determination of the initial and final state in nucleon structure and spectroscopy investigations. The recently awarded project grant for the JLab Upgrade cements the UK's position in this field, building on past excellence and projecting it towards the future and new, emergent opportunities like the Electron Ion Collider initiative.

The study of fundamental QCD requires the study of freely moving quarks and gluons, the quark-gluon plasma. Its study provides a unique environment to tackle many pressing questions in our understanding of the strong interaction. Following successful experiments at RHIC, new results are produced by the ALICE collaboration at CERN, with an increasing footprint of UK institutions, enabled by the recently awarded project grant to contribute to the upgrade of the ALICE detector system.

Nuclear Theory

Theoretical developments, especially for *ab-initio* and nuclear mean-field, rely on the availability of supercomputer resources. The advent of STFC's DiRAC High Performance Computing Facility, with capital funding from BIS and now in Phase 2 (2012-2015), has allowed UK lattice theorists to make huge strides forward with their international collaborators. Funding for Phase 3 of DiRAC is now being sought,

focusing on 3 architectures to support the range of calculations planned across theoretical particle, nuclear and astrophysics.

A valuable resource for UK Theory in the ECT* institute at Trento, Italy. A series of workshops is organised each year covering a wide range of nuclear physics topics with an emphasis on theory. For example, during 2016, there will be 18 one-week long workshops some of which will bring experiment and theory together. The UK has taken leadership on organising a number of workshops, e.g. four during 2015. Theorists are also encouraged to visit the facilities at ECT* either to work with the in house group or to have informal meetings with colleagues. **STFC should continue to support UK membership of ECT*.**

Summary

A summary of the characteristics of the facilities and devices used by the UK nuclear physics community:

- High-intensity stable beam accelerators for nuclear spectroscopy and time-extended direct measurements of nuclear reaction cross sections
- ISOL facilities for reactions involving exotic nuclei
- Fragmentation facilities to measure properties of exotic nuclei
- Charged particle and gamma-ray detector arrays (e.g. AIDA, AGATA, FATIMA, GREAT, LYCCA ...)
- Nuclear recoil separators
- High-intensity polarised electron accelerators over a wide range of energies for nucleon spectroscopy and scattering experiments
- Fast tracking and particle identification detectors
- Trigger and slow control systems
- High-Performance Computing (HPC) centres

Recommendation: There must be strong support for physics exploitation at appropriate world-leading facilities. NPAP recommends an increase in support for exploitation in the CG round.

2.1 Radioactive Beam Facilities

By their very nature, radioactive nuclei, especially those with short (less than a few days) half-lives, are not readily available and must be produced in the laboratory before further experiments can take place. Such nuclei can be produced in many different ways, each with its own set of pros and cons depending on the requirements of the scientific cases at hand and the specific experimental techniques employed to address them.

2.1.1 ISOL-type Facilities: Precision Frontier

Low-energy (<60 keV) radioactive ion beams produced at isotope separator on-line (ISOL) facilities such as ISOLDE-CERN and ISAC-TRIUMF have high purity, high quality (low energy spread and emittance) and high intensity properties. These properties are essential for a range of experimental techniques, such as decay spectroscopy, laser spectroscopy and re-acceleration. Within Europe, ISOLDE is the world leading ISOL facility with access to over 700 radioactive beams with half-lives down to milliseconds. The IGISOL facility at the University of Jyväskylä utilizes gas catching techniques to access elements that are not readily available at ISOLDE and therefore provides a complementary tool for refractory cases.

- ISOL beams are particularly well suited for high-resolution laser spectroscopy techniques that measure nuclear observables. Such experiments require a long-term commitment at a facility to develop the apparatus. The UK has strong leadership in this field and is active both at ISOLDE (CERN) and ISAC (TRIUMF) facilities. Trapping techniques developed by the UK at the IGISOL facility (Finland) have been exported around the world and are now routinely used.
- ISOL beams are ideal for re-acceleration purposes so as to meet the specific energy requirements of the experimenters. ISOLDE is being upgraded in the HIE-ISOLDE programme to deliver beams of up to 10 MeV/u. The upgrade to 5 MeV/u in 2015 allows measurements of transfer reactions on light-exotic nuclei. The ISOLDE collaboration has recently committed funding for a third beam line to

allow the STFC-funded solenoid spectrometer to be installed and operated as part of the HIE-ISOLDE project. The UK also has a number of active research collaborations with the SPIRAL facility at GANIL and at TRIUMF using both the ISAC I and ISAC II facilities, and a suite of state-of-the-art devices such as DRAGON and VAMOS (recoil separators), SHARC (highly-segmented silicon detector array), EMMA (recoil mass spectrometer), and both EXOGAM and TIGRESS (gamma-ray spectrometers).

- In the medium term the UK will also be looking to exploit the SPES facility at LNL (Italy), in particular utilising the AGATA gamma-ray spectrometer, and FRIB at NSCL in the US and in the longer term with EURISOL in Europe.

2.1.2 Fragmentation-type Facilities: Isospin and Mass Frontier

Fragmentation facilities are best suited for discovery type experiments that extend our knowledge to the most exotic of nuclei. This is due to the fast (μs) transport from the site of production to detection and to the independence from chemical effects inherent in the fragmentation method. There is a significant programme of research at existing fragmentation facilities through UK-led experiments at GSI using NUSTAR-developed instrumentation. The UK has led the development of new techniques at fragmentation facilities such as using knockout reactions at NSCL to study charge-symmetry breaking effects in nuclei.

- Within Europe, FAIR at GSI will have the ability to cool and trap relativistic fragmented beams providing complimentary access to intense exotic beams that cannot be produced at ISOL facilities. The existing GSI fragmentation facility will provide beams while FAIR is constructed. The beam intensities will be improved compared with previous campaigns, primarily through the upgrade of the SIS-18 synchrotron. The UK has taken a leading role in the precision measurement sector of the FAIR project. The UK has made a substantial investment in the instrumentation for HISPEC, DESPEC and R3B required for NUSTAR. NUSTAR-developed equipment and techniques are being/will be exploited at current and future facilities, maximising the physics potential ahead of the startup of FAIR.
- RIBF at RIKEN (Japan) is currently the leading fragmentation facility in the world, with the highest beam intensities (for $Z < 60$) at the limits of nuclear existence. It dominates the study of exotic (neutron/proton rich) nuclei. Decay spectroscopy (gamma-ray detectors and beta delayed neutron detection), Coulomb excitation, and secondary fragmentation are very active programs, studying the most neutron- and proton-rich nuclei (up to $Z \leq 60-66$). Deep-inelastic reactions are planned to study neutron-rich $N \sim 126$ nuclei. The UK is involved in all these activities with high visibility and leadership roles.

2.2 Stable Beam Facilities for Nuclear Structure and Nuclear Astrophysics

Bespoke stable beam facilities maintain a vital role in nuclear physics research. They provide unique access to high-intensity and high quality beams and when combined with state of the art spectrometers provide unique tools to study the single particle properties of the nucleus. The UK Nuclear Physics community has been to provide state-of-the-art techniques and detectors to make step changes in sensitivity. At the University of Jyvaskyla, tagging methods continue to be developed to enable access to structural information at the very limits of proton binding. Two areas of UK research leadership are investigating the limits of existence for proton-rich nuclei and superheavy elements, both of which depend upon access to facilities such as Jyvaskyla and GSI. In addition to nuclear structure and nuclear astrophysics, transfer-reaction measurements with stable light-ion beams have direct application in constraining calculations of neutrino-less double beta decay ($0\nu\beta\beta$ matrix elements) which will allow the absolute mass of the neutrino to be determined if $0\nu\beta\beta$ decay is observed. The ability to test, with precision measurements, the ingredients of *ab-initio* calculations containing realistic forces against the structure of light nuclei is critically important. The UK is leading research at the frontier of discrete-line gamma-ray spectroscopy at ultra-high spin, and has made precision studies of the behaviour of several rare-earth systems at the highest spins, investigating competition between single-particle excitations and the many collective structures that occur. This field has recently undergone a renaissance of experimental and theoretical interest with the discovery of collective structures that are associated with rotating triaxial nuclei at ultrahigh spins.

The UK programme of research using high-intensity stable beams uses facilities such as ANL, the University of Jyväskylä, Munich, Orsay, RCNP-Osaka, GANIL and LNL, and employs spectrometers such as GAMMASPHERE, JUROGAM and AGATA.

For low-energy stable-beam experiments in nuclear astrophysics, additional requirements must be fulfilled to maximize the signal-to-noise ratios: high beam intensities (hundreds of μA currents); ultra-pure targets (to minimize beam-induced background); high detection efficiency for charged particles, neutrons, and gamma rays; long measuring times; and ad-hoc experimental techniques. All of these can only be attained at dedicated facilities, ideally underground. The Laboratory for Underground Nuclear Astrophysics (LUNA) at Gran Sasso (Italy) remains to date the only facility of its kind worldwide and maintains a pioneering leadership that spans across the last two decades. Further breakthroughs are expected to come from its upgrade to a new LUNA MV accelerator, which will allow for studies of helium and carbon burning reactions, as well as key reactions that provide the neutron source for the s-process.

2.3 Hadron Physics Facilities

Probing the smallest constituents of matter requires projectiles of appropriately small wavelength and thus high energy. To make precision studies of the bound states of QCD, high-energy electron beams or photon beams are required. To study the high temperature and high density phase of strongly interacting matter, high-energy hadron beams, particularly heavy nuclei, are required. The hadron physics community utilises a number of experimental facilities in Europe (MAMI; the LHC at CERN, Switzerland) and in the US (Brookhaven National Laboratory; JLab). Two recently approved hadron physics projects: the JLab Upgrade to 12 GeV and the ALICE Upgrade at the CERN LHC, have consolidated the UK community's position in this field and strengthened strategic links with these two world-leading facilities.

2.3.1 Electron Beam Facilities: Precision Frontier

JLab provides polarised electron beams and real photon beams with circular and linear polarisation and energies up to 12 GeV. Its experimental programme is delivered in four halls, with UK scientists active in each of them. The JLab Upgrade project is enabling UK groups to make a significant impact in the science programme at the upgraded facility, capitalising on current leadership roles in the future programme, and exploiting the synergies of leading research with two key upgrade systems: CLAS12 in Hall B and the Super Bigbite Spectrometer (SBS) in Hall A. This contribution to the world's leading hadron physics facility permits continued leadership of science in the areas of hadron spectroscopy and nucleon structure and paves the path to a future, strong UK involvement in the JLab nuclear physics programme and beyond.

2.3.2 Hadron Beam Facilities: Energy Frontier

The LHC at CERN allows the study of proton-proton collisions at a centre-of-mass energy of 13 TeV and proton-lead and lead-lead collisions at centre-of-mass energies of 8 and 5 TeV per nucleon, respectively. The energy density achieved in the early stages of lead-lead collisions is unprecedented in the laboratory. It is estimated to be 50-100 times that of normal nuclear matter, offering unique insight into the bulk matter properties of QCD and the confinement phase transition. The ALICE Upgrade project has enabled UK groups to maintain and establish new areas of technical and scientific leadership within the experiment – leading the upgrade of the central trigger system and making a significant contribution to the mechanical design and construction of a new inner.

The areas of scientific and technical expertise outlined above will put the UK in a strong position as the international hadron physics community begins to consider its long-term future priorities beyond the exploitation of the upgraded facility at JLab and the new opportunities presented by operating ALICE at higher data rates at the LHC.

2.4 Equipment Development

Access to the many international facilities used by the UK nuclear physics community worldwide 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 normally made available to other facility users. Research at experimental facilities is by necessity underpinned by the development of state-of-the-art detection systems. The UK continues to be identifiable internationally as a partner of choice in major experimental programs that are critical to the delivery of the next generation of Nuclear Physics experiments. The development of state-of-the-art instrumentation is vital for the subject to sustain itself and to maintain the viability and credibility of the UK for the future. Specific examples are given below.

- The UK has recently completed the development of key mechanical components and instrumentation for the HISPEC, DESPEC and R3B experiments at the future NuSTAR experiment at the FAIR facility. The LYCCA array for HISPEC has been used as part of the recent AGATA-Prespec campaign at the GSI facility. The FATIMA fast timing array for DESPEC has been deployed at RIKEN and ANL for a series of successful experiments. Both will be deployed at GSI.
- The AIDA (Advanced Implantation Detector Array) system is now commissioned at RIKEN, and is being coupled to different devices to study decays of r-process nuclei. This will be a long-term programme until AIDA will eventually be employed at FAIR by the NuSTAR collaboration as part of DESPEC. A smaller scale system based on the AIDA system may be deployed at GSI in the next 2-3 years depending on availability of beams at GSI.
- The UK has made a significant contribution to the AGATA (Advanced Gamma Tracking Array) spectrometer which has been used in physics campaigns at LNL and at GSI and is currently being upgraded and utilised in a major physics campaign at GANIL. STFC has signed the international memorandum of understanding (MOU) which specifies the further development of the array to include 60 detectors.
- The UK in collaboration with GSI, Heidelberg, and Frankfurt have formed a new collaboration to promote and co-ordinate the use of heavy ion storage rings for nuclear astrophysics NucAR. This will complement efforts at GSI using the ESR, and in developing the in-ring detection systems for the UK ISOL SRS project within the TSR@ISOLDE collaboration.
- The UK have become members of the n-TOF collaboration at CERN to exploit intense neutron beams for nuclear astrophysics, and are building a new chamber for charged particle reactions induced by neutrons on the new EAR (Experimental Area) 2 beam-line. The STEFF spectrometer has been installed and commissioned at the n-TOF facility.
- A purpose-built reaction chamber equipped with an array of large area silicon detectors was developed and successfully exploited for underground studies at LUNA of (p,α) reactions important for the synthesis of rare isotopes in Asymptotic Giant Branch (AGB) and massive stars.
- The Glasgow electron tagging spectrometer and the Edinburgh Particle Identification detector at MAMI are an integral part of the real photon experimental programme and a sine-qua-non for its current research.
- UK expertise in the generation of linearly polarised photon beams is crucial for the success of the GlueX experiment at JLab's Hall D.
- Fast particle identification and tracking systems developed in the UK are integral for the current physics programme at JLab.

The UK Nuclear Physics community should be supported to continue to exploit its leading position in instrumentation technology in focused areas through continued investment in new projects. This is essential to the long-term future of the field and provides substantial opportunity for broader societal impact.

3 LEADERSHIP AND FUTURE OPPORTUNITIES

3.1 Nuclear Structure and Astrophysics

3.1.1 Involvement and Leadership

UK Involvement:

45 Academics at 8 Institutions (Birmingham, Brighton, Edinburgh, Liverpool, Manchester, STFC Daresbury Laboratory, Surrey, UWS, York)

UK Leadership: (selected examples)

- NUSTAR Board of Representatives
- NuPECC Long Range Plan (LRP) Science Convenors (Nuclear Structure and Nuclear Astrophysics)
- The UK has provided the chair (elected) for the AGATA management board, steering committee and AGATA Collaboration Council
- Spokespersons of the AGATA, ILIMA, SHE (super-heavy elements) and HISPEC/DESPEC collaborations
- HIE-ISOLDE Steering Committee membership
- Spokespersons of experiments at many international facilities
- Chairs of the ISOLDE and Neutron time-of-flight committees
- The external head of the heavy ion reaction group at TOKIA
- Invited chair and representation on the Programme Advisory Committees for a wide range of international facilities
- Deputy Spokesperson, Physics Coordinator and three physics convenors within the Heavy Ion storage ring (TSR) collaboration
- Membership of LUNA Collaboration Board and Chair of LUNA Editorial Board

3.1.2 Current project

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. The main goal of the project is to build a spectrometer for the measurement of charged-particle reaction products to the Helical Orbit Spectrometer, employing high granularity silicon-detector systems. The detector system will enable the whole range of radioactive nuclei accelerated by HIE-ISOLDE to be studied with unsurpassed energy resolution and sensitivity, in future taking advantage of the superior properties of the radioactive beam cooled within the ring.



Figure 4: Helical Orbit Spectrometer, ex-MRI magnet delivered to CERN ISOLDE, April 2016

Science Reach: What are the Origins of the Elements? What are the nuclear processes, and main astrophysical sites, that produce the γ -ray emitting radionuclides observed in our galaxy?

What is the Nature of Nuclear Matter? What are the limits of nuclear existence? How do simple patterns emerge in complex nuclei?

Scientific Leadership: Physics coordinator 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 advances will stem from 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 MRI magnet obtained from Australia to create a first generation helical spectrometer for ISOLDE.

Institutions: 8. Academics: 32 Project value: £3M

3.1.3 Future Opportunities

Crucial to the sustained leadership and advancement of the UK nuclear physics community is access to upcoming state-of-the-art facilities and a strategic connection to the opportunities that they offer. Many of these new facilities will begin delivering beams within the next 10 years and represent an excellent opportunity for the UK. The intellectual capital gained through focussed projects such as AGATA, NuSTAR and ISOL-SRS, as well as the existing exploitation programmes elsewhere, all provide the UK with significant influence and access opportunities for further advances in the field. Some of the key upcoming facilities are listed below according to the expected time of operation. In parentheses, the expected time for commissioning/operation.

- FRANZ (2016): University of Frankfurt in Germany, is an ultra high neutron flux facility, which will provide the highest stellar neutron flux worldwide. FRANZ will allow a variety of measurements on short-lived nuclei (half lives down to months) using the time-of-flight or the activation method.
- GANIL (2018): The Super Separator Spectrometer (S3) facility (2018) at GANIL (France) and the ability to deliver clean refractory beams to a low energy experimental area (DESIR) represent an excellent opportunity to extend precision measurements such as laser spectroscopy to the proton drip line.
- LUNA MV (2018): Upgrade of existing LUNA facility. Will consist of a new 3.5MV accelerator capable of delivering high-intensity proton, alpha particle, and ^{12}C beams for low energy nuclear reaction studies (helium burning and neutron sources) at the underground laboratory at Gran Sasso.
- ARIEL (2018): Is a high-powered superconducting electron LINAC at TRIUMF National Laboratory in Canada that will allow for the delivery of intense, high-quality neutron-rich beams to the ISAC-II hall for studies of shell model evaluation and r-process nucleosynthesis.
- ELI-NP (2018): The Extreme Light Infrastructure – Nuclear Physics facility in Romania. The facility's Gamma-Beam System (GBS) will yield unique opportunities for nuclear physics. It will deliver a high-intensity polarised gamma-beam of up to 19 MeV.
- SPIRAL 2 Phase 1 (2020): Planned upgrades to SPIRAL at GANIL include expanded capability to deliver high intensity new and existing radioactive beams at lower energies relevant for direct measurements of key nuclear reactions for explosive nucleosynthesis.
- SPES (2020): The first two phases of the SPES facility at LNL are now fully funded and will provide low energy ISOL beams for decay spectroscopy and precision measurements.
- TSR@CERN (2022): Reaction measurements on a storage ring using RIBs injected from the HIE-ISOLDE facility, with an expected 6-orders-of-magnitude gain in beam intensities.
- FAIR (2022): Next generation European Fragmentation facility at GSI. Campaigns of experiments as part of the NuSTAR collaboration using HISPEC, DESPEC and R3B.
- FRIB (2022): At Michigan State University in the US, is a next-generation fragmentation facility designed to produce intense beams of rare isotopes. Such intensities will allow for the investigation of many astrophysical reactions that have hitherto remained inaccessible.

3.1.4 Future Projects (mid-term)

Scintillator tracking array (STA): A future portable tracking array for use at RIKEN. The STA project aims to produce a highly modular array based on next-generation scintillators coupled to silicon photomultipliers. The energy and position resolution will be matched to the resolution imposed by the properties of the secondary radioactive beams at RIBF-RIKEN and with the aim to upgrade and replace the existing DALI-2 array. This technology is insensitive to magnetic fields and could be developed for gamma-ray detection inside the solenoidal spectrometer being constructed for use at HIE-ISOLDE, CERN.

Institutions: 4. Academics: 15 Estimated project value: £2.5M

Advance charged-particle array (ACPA): The ELI-NP Gamma-Beam System (GBS) includes the EU-funded electron accelerator being built at STFC Daresbury Laboratory under contract with INFN. The first stage of the GBS is planned for commissioning at ELI-NP in 2017, with the remaining commissioned in 2019. However, there is further scope for a UK lead in detector developments for the ELI-NP GBS, benefitting from the UK detector expertise. This could include an advanced charged-particle array for nuclear astrophysics, as well as a gamma-ray detector system for structure studies including gamma-fluorescence. Further, building on the GBS high-intensity electron accelerator, there may be potential for the development of an electro-fission ISOL facility at ELI-NP.

Institutions: 3. Academics: 10 Estimated project value: £1.5M

AGATA upgrade: The UK will use its internationally recognised leadership in the realisation of detector systems and their associated ancillary detectors. These developments will create a device with greater solid angle and a significantly enhanced science reach in terms of improved sensitivity. This will fulfill the UK's intended commitment as outlined in the AGATA MOU.

Institutions: 6. Academics: 20 Estimated project value: £2.5M

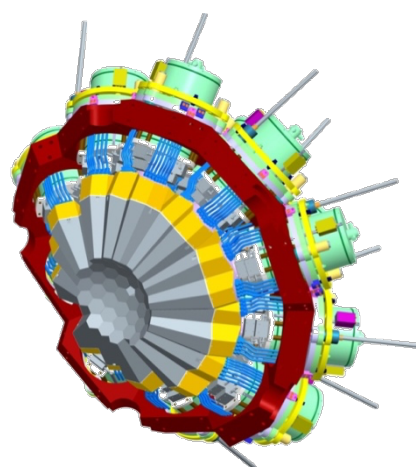


Figure 5: Schematic diagram of the AGATA spectrometer

3.1.5 Future Projects (Horizon)

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. However, between the construction of EURISOL and the current generation HIE-ISOLDE and SPIRAL2 there are expected to be upgrades at existing facilities.

The UK is associate member of FAIR. According to the current plans, FAIR will deliver its first beams in around 2022. It will produce intense, high brilliance beams of all chemical elements up to uranium with energies in the range $E \sim 1-30$ GeV per nucleon and also antiprotons. Such beams and FAIR's unique infrastructure (eg storage rings) will provide capabilities unmatched worldwide, especially regarding the study of heavy elements. Equipment built on the NUSTAR and AIDA grants is exploited presently at the RIKEN fragmentation facility in Japan and ANL in the USA. Experience will be gained there as well as other facilities, including the existing GSI at the site of FAIR. Based on these, and future developments in detector technology and electronics, an NUSTAR upgrade project is envisaged in the future. This will likely include support for the dedicated decay spectroscopy gamma-ray array at DESPEC.

3.2 Hadron Physics

3.2.1 Involvement and Leadership

UK Involvement:

10 Academics at 5 Institutions (Birmingham, Edinburgh, Glasgow, Liverpool, STFC Daresbury Laboratory)

UK Leadership:

- CLAS (JLab Hall B) collaboration chairperson
- Leading position in EU *Hadronphysics 1-3* research initiatives
- Spokespersons, analysis- and project leaders at JLab, MAMI, DESY
- Strong representation at collaboration management levels, technical boards and subsystem leaders
- ALICE Physics Work Group convenor (Light Flavour, Ultra-peripheral and Diffraction)
- ALICE Physics Analysis Group convenor (Strangeness)

3.2.2 Current projects

The JLab Upgrade project is developing key elements of a Forward Tagger for CLAS12 in Hall B, and the Super Bigbite Spectrometer (SBS) in Hall A.

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. Chair of CLAS hadron physics working group, member of CLAS Coordinating Committee. Approved experiments with CLAS12 and Hall A.

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 Project value: £1.5M

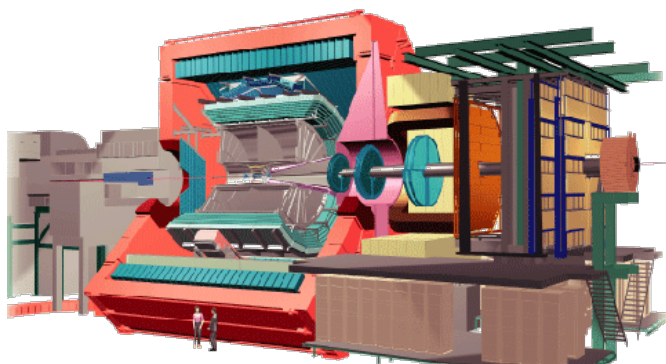


Figure 7: The ALICE experiment

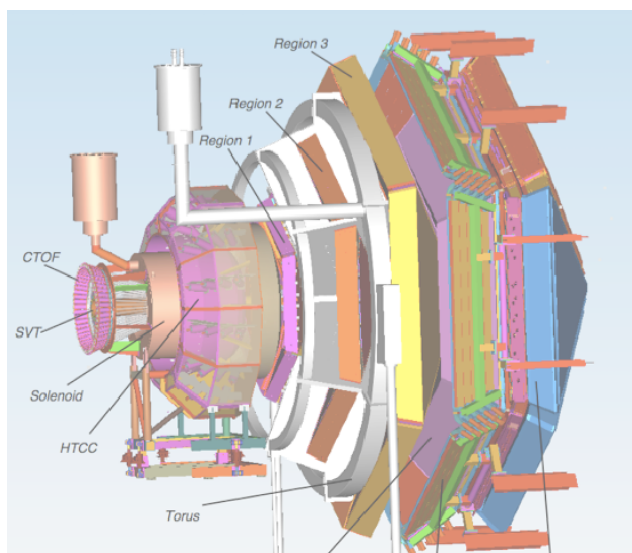


Figure 6: A schematic diagram of the CLAS12 detector

ALICE-Upgrade: The UK is playing major role in the upgrade of the Inner Tracking System (ITS).

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.

Technological Expertise/Drivers/Impact: Developing a large scale silicon detector and a new trigger system for ALICE.

Institutions: 3. Academics: 4 *Project value: £3M*

3.2.3 Future Opportunities

In the coming decade, the hadron physics community in the UK will concentrate its exploitation efforts on the high precision electron beam experiments that have become possible at the upgraded facility at JLab and on the opportunities presented by the upgraded ALICE detector at the LHC. In parallel, the community will be strongly engaged in defining the physics case for a future EIC and to foster their strength in the development of detector and trigger systems for the EIC detector systems.

Future work on understanding the structure of hadrons via spectroscopy will concentrate on exploiting the experimental opportunities opened up by the use of polarised beams and polarised target as well as high luminosity and large acceptance precision experiments; mainly at MAMI, for the lower lying resonance states and states predominantly decaying into neutral particles and at JLab for higher energies and all particle final states. This work will realise many so-called complete experiments in the photo production of pseudo-scalar mesons, the exploitation of the rich meson yield from the current and future CLAS experiments and the beginning of precision spectroscopy using the GlueX spectrometer. These results will further clarify the existence or non-existence of predicted baryon resonances as well as aiding the search for new, exotic mesonic states within and outside the current meson models, e.g. Hybrid states, meson molecules and Glueballs, which are predicted to exist by Lattice QCD, but where experimental evidence so far has been scarce. Nucleon structure experiments will use the precision offered by the upgraded facility at JLab and continue the study of multi-dimensional parton distributions in semi-inclusive and exclusive reactions, aiming at a full description of the partonic content of nucleons in momentum and space in the valence quark region. Further opportunities will arise with new experiments in Halls B and D at JLab as well as cross-experimental analysis efforts, in particular on partial wave analysis, between the CLAS, GlueX, PANDA and other possible collaborations. This will include the new SoLID detector for which the UK has a significant role in the simulation and design of the detector. SoLID would allow measurements with large acceptance at close to the maximum luminosity of JLAB12, extending the physics reach of the nucleon structure programme, particularly for parity violating electron scattering measurements. Physics runs with 12 GeV electron beams at JLab are expected to start in 2017.

Future work directed toward the understanding of hot QCD matter will exploit the higher data rate and high granularity tracking capability of the upgraded ALICE detector. The upgrade will be completed in 2019-20 for LHC RUN3 in the period 2021-23. ALICE will continue to take data until at least 2029. The focus of the UK groups will shift to the analysis of rare probes, particularly the production of heavy flavour (charm and bottom quarks) and hard scattered quarks and gluons leading to jets. The primary physics objective is to understand the transport of energy and momentum in a deconfined, dense system of quarks and gluons. The production of heavy quarks and jets during the early stages of a collision is governed by processes that involve a large momentum transfer. This is a regime in which perturbative QCD calculations are valid and as such these processes give direct access to the fundamental constituents before the formation of the quark-gluon plasma. Their evolution is governed by the thermalisation of heavy quarks and the attenuation of fast, scattered gluons and light quarks in the ensuing plasma phase. The fates of these rare probes are predicted to be most sensitive to the transport properties of the quark-gluon plasma. Therefore, the study of charm and bottom hadrons and the modification of jets, amongst a wide range of other measurements, will permit a detailed exploration of the dynamical properties of matter at high parton density.

The next experimental facility for precision studies of the strong interaction will be the planned EIC, vastly extending the capabilities of current machines by using high energies, large kinematical coverage, precision detection of final states and exploiting polarisation degrees of freedom. UK scientists will take

a leading role in defining the physics case and detector systems, starting with phenomenological and simulation studies in 2016, leading to an extensive R&D programme in tracking and particle identification detectors and trigger systems from 2019 onwards.

3.2.2 Future Projects (Horizon)

In the ten years' timescale of this Nuclear Physics Roadmap, future opportunities will principally emerge from the investment that is currently being made to exploit 12 GeV electron beams at JLab and high energy, high luminosity hadron beams at the CERN LHC.

The next major hadron physics facility looks likely to be a high-energy Electron-Ion Collider (EIC) to be constructed in the US. The EIC has recently been endorsed as the highest priority new build nuclear physics facility in the 2015 NSAC Long Range Plan. The timescale of this project is subject to US planning and approval, but commissioning and early physics is possible between 2025-2030. The first step in the approval process is for the facility to achieve Critical Decision Zero (CD0) status, establishing *mission need*, which may take place in the next 2-3 years. The proposed facility will provide electron-proton collisions with polarised electron and polarised proton beams, and electron-ion collisions with polarised electrons and a variety of unpolarised heavy-ion beams. This new machine will bridge the gap between the new high precision results expected from JLab with the higher energy results already obtained from HERA, widening the physics reach of both by a larger kinematic range, a full exploitation of polarisation and a wide range of strongly interacting targets. A feature of this new facility will be its unparalleled luminosity allowing an exquisitely detailed exploration of the spatial and momentum distributions of quarks and gluons in the nucleon at very short distances where the gluon distribution dominates. It will also allow the exploration of an entirely new QCD regime in which the gluon density in heavy nuclei is expected to become saturated. This facility will not only address fundamental questions in nucleon structure, and the spin of the nucleon at short distances, but also the partonic structure of nuclei, the onset of gluon saturation and the propagation of partons in cold nuclear matter. As such, its potential science reach encompasses the current research interests of all groups within the UK hadron physics community. Members of the community with interest in both electron-proton and electron-ion physics are currently preparing a statement of intent on a common future involvement in the design, construction and physics programme of experiments at this facility.

3.3 Nuclear Theory

3.3.1 Involvement and Leadership

UK Involvement:

10 Academics at 3 Institutions (Manchester, York, and Surrey)

UK Leadership:

The UK has an international reputation in reaction theory, which has long provided support to world leading laboratories, including NCSL at Michigan state University. This is now matched by the new theory group at York who are among the world leaders in the development and exploitation of nuclear density functional theory. The UK has leadership in studies of hadron structure and applications of effective field theories. The strong international programme in ab-initio theory has grown rapidly in the past few years, through developing and applying state of the art Green's function theory and coupled cluster methods to a variety of problems in finite and infinite matter.

3.3.2 Future Opportunities

The STFC has founded a new initiative to strengthen the national and international role of the UK theory community. This effort is nicknamed [Nuclear.Theory.Vision@UK](#) and it is led by Prof. Jacek Dobaczewski. It will concentrate on three main activities over the years 2015 to 2018:

- Training of students on advanced theoretical topics. Three international summer schools are planned within the TALENT programme, which provides training for students and PDRAs. These

will begin with the 2016 TALENT school on “*Density Functional Theory and Self-Consistent Methods*” that is being held at York in July 2016.

- A visitor programme will attract high-profile international theorists to the UK. The aim is to foster new world leading collaborations and to provide contact with local UK experimenters.
- Regular bi-annual theory meetings will be held at the three theory institutions to discuss advances within the community, with participation from experimenter. A key goal is to increase the interactions and collaborations between the UK experimental and theory communities.

With the present intellectual environment, the UK theory community will seek to further leadership roles over the next few years. Opportunities from the advent of new facilities will demand advances in reaction theory on several fronts. In an international setting in which reaction theorists are in demand, the UK could easily capitalise on its expertise and expand the efforts in this sub field. The DFT and *ab-initio* groups have a unique opportunity to pursue a new generation of EDFs that are derived from first principles. On the one hand, first principle calculations are necessary, for example to address data on radii and masses coming from ISOLDE (CERN) and TITAN (TRIUMF) and data on nuclear correlations from R3B (GSI) and RIKEN. On the other hand, new and more accurate functionals will open path to addressing several question in heavy nuclei and specific reactions governing nucleo-synthesis. Applying *ab-initio* theory to test our understanding of the nuclear force (with links to the EFTs and calculation from the international Lattice QCD community) will also be beneficial to improve predictions of neutron star matter and astrophysical objects.

3.3.3 Long-Term Vision

Nuclear theory plays the dual role of guiding and supporting experimental efforts and of developing and advancing new theoretical tools for the investigation of nuclei. With high quality data expected from current and future experiments and reaching into new territory, Nuclear Physics 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 experiments.

Over the coming decade, our priority will be to tackle the most important scientific questions. Given the already broad spectrum of present interests, the initial step will be to consolidate the UK leadership in the five areas already covered by the community: reaction theory, nuclear DFT, EFT and hadron structure, *ab-initio* methods and applications to nuclear astrophysics. To this aim, it will be crucial to continue to innovate on techniques for nuclear reactions, structure calculations and EFTs. The unprecedented precision of data expected from new facilities call for the substantial use of *ab-initio* approaches and the exploitation on HPC. The other major challenge will be to grow the involvement with and support to the UK led experimental program. This can be achieved most effectively with a continuation of the Nuclear.Theory.Vision@UK initiatives beyond 2018 but it will also require a larger academic and postdoctoral base within the country.

It remains clear that cutting edge theory requires first of all postdoctoral manpower and then continuous collaborations with international researchers and teams at overseas facilities. Normally, theorists require similar levels of mobility/involvement as experimentalists. In order to support the existing theory community support with appropriate levels of postdoctoral posts and research studentships should be prioritised based on the quality of the scientific case. Major new initiatives (with UK leadership) are only possible if this support is present, together with the necessary resources for travel and access to high performance computing (HPC).

Recommendation: The UK should support flagship projects in Nuclear and Hadronic physics including upgrades that capitalise on previous investments and maximise high-quality science output and UK leadership in international projects, with an appropriate uplift in funding to support a balanced programme.

Recommendation: The funded programme going forward should support the R&D and design-stage activities that are likely to offer significant future scientific opportunities.

Recommendation: Support for an appropriate portfolio of smaller-scale high-quality projects that capitalise on UK leadership capabilities, add diversity and novelty, and which provide excellent scientific return for modest investment.

4. UK NUCLEAR PHYSICS STANDING AND IMPACT

4.1 The UK Nuclear Physics Community Makeup

The nuclear physics research community in the UK is comprised of 65 academic staff at 10 institutions. The community is supported by approximately 60 research and professional staff and a further 90 research students (of which approximately 48 are funded by STFC). The broad ratio of the size of the community relative to that of Particle Physics and Astronomy is 1 : 4 : 6, respectively. The UK nuclear physics programme is ranked first in the world by measure of its impact and citations, STFC IMPACT Report 2015. The performance of the UK community is shown in table 1.

Nuclear physics	2008	2009	2010	2011	2012	2013
Number of publications	372	347	347	296	489	496
UK position	7	7	7	7	7	7
Citation Impact (CI)	6.47	6.99	6.74	13.00	16.00	15.40
UK position	2	2	2	2	1	1
Normalised Citation Impact (NCI)	1.51	1.55	1.62	1.72	5.12	3.10
UK position	2	2	2	2	1	2

Table 1: The performance of the UK Nuclear Physics community

The current UK Nuclear Physics programme is funded through consolidated grants in addition to three funded projects ISOL-SRS, Jlab-Upgrade and ALICE-Upgrade. Experimental work utilises equipment funded through earlier EPSRC/STFC grants. Exploitation is currently the largest component of the research programme.

The balance of the programme taken from the last consolidated grants round can be seen in table 2. It excludes the York theory group which was funded separately. The associated nuclear physics budget is approximately £6.2M per year and has remained flat. It is split approximately into 78% exploitation and 22% development (e.g. R&D/construction projects), a budget of £4.84M pa for exploitation and £1.36M pa for development, respectively. In addition to the above, the funding for Nuclear Physics Studentships and Fellowships is £1.1M pa.

	% of Themes	% of PDRAs (by FTE)	% of Academics (by FTE)
Nuclear Structure	64%	62%	68%
Nuclear Astrophysics	16%	13%	14%
Hadron Physics	20%	25%	18%
Total	100%	100%	100%
Experiment	89%	87%	83%
Theory	11%	13%	17%
Total	100%	100%	100%

Table 2: The balance of the Nuclear Physics Programme taken from the last consolidated grants round

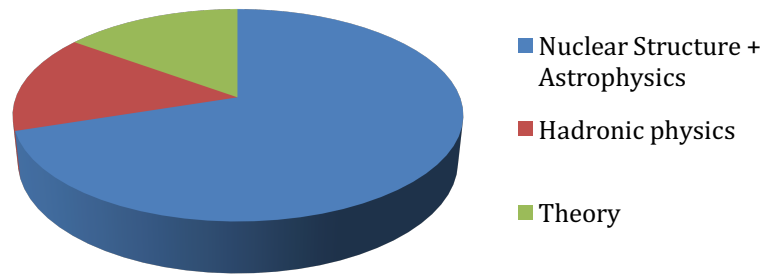


Figure 8: Theme areas studied by academic staff

The current distribution of the community (per academic) among subject areas in the Nuclear Physics programme is shown in Figure 8.

4.1.1 Cross-Community Support

One of the reasons why the UK community is welcomed at international experimental facilities is its expertise in the development of state-of-the-art instrumentation. This is vital for the subject to sustain itself and to maintain the viability and credibility of the UK for the future.

This is achieved by the UK having a group of leading scientists and engineers who have many years' experience of developing and operating detectors, instrumentation and spectrometers. They are involved in the design of new detectors and instruments and work closely with other international collaborators throughout the life of a project. The engineers are experts in their own fields and lead the development and commissioning of the new detectors and instruments at the international laboratories and once a system is installed they have a responsibility for its maintenance during the lifetime of its operation, in particular to help diagnose and repair unforeseen faults. The cross community team has successfully installed many detector systems for the UK. The work of this group has made a dramatic impact at a number of overseas laboratories and, as a result, many members of the group have established a well-deserved international reputation for their expertise in specific areas of technology. These experts are also often called upon by the UK academic community in the early stages of new projects to verify ideas and provide advice on experimental proposals.

The importance of this body of expertise was first recognised by EPSRC who set up an engineering and instrumentation team to underpin the UK experimental programme. This was continued by STFC, supported by the NPGP, in the rolling and consolidated grants rounds by the support of a cross-community pool of expertise. This body comprises teams of mechanical, electronics, software engineers and a target technician. The cross community effort is based at STFC Daresbury Laboratory and the Universities of Liverpool and Manchester.

An asset of the UK community is the technical and engineering expertise within STFC, which is either in or through the Nuclear Physics Group at Daresbury. Indeed, the group's primary role is to provide scientific, technical and engineering expertise to support and co-ordinate the programme of research and projects funded by STFC in the field of nuclear physics for the whole UK community.

At the time of the last consolidated grants round by the NPGP in 2014 the major projects ISOL-SRS and ALICE were also in the process of being reviewed. The outcome was that the overall level of effort needed for both the funded consolidated grant themes and the project grants significantly exceeded the amount funded.

Recommendation: NPAP recommends that different STFC panels, such as NPGP, PPRP and the cross community committee, work together in order to ensure that approved projects and science themes are properly funded.

4.2 Applications and Innovation

Historically, nuclear physics has made important contributions to applied science for the benefit of society. The first accelerators were developed to study nuclear phenomena and more recently proton and carbon beam cancer therapy being 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 (SPECT, PET, MRI).

The Nuclear Physics community continues to have a very productive collaboration with industry, the majority of UK institutions have significant industrial engagement programmes which support knowledge exchange and the development of future REF returnable impact cases. A number of these activities have been highlighted in STFC publications and the national press. The recognised international strength of our instrumentation and innovation personnel that support both the science and impact programme are essential to this success.

Example case study 1: University of York & Kromek

The University of York have developed a hand-held gamma-ray detector based on an SiPM array coupled to a CsI(Tl) scintillator for Kromek. This built on earlier funded work e.g. NuPNET project from STFC. The detector led to a product called SIGMA sold by Kromek and is now part of a device called D3 which is intended to be worn by the law enforcement community etc. in the US to monitor for radiation in the field. Kromek are presently supplying a thousand such devices to the US government with the expectation of an order for 10,000 in the next year. This work was followed up with a mini-IPS project to further improve the performance of the SIGMA probe. York are also part of a US DTRA project with Kromek to develop similar systems based on next-generation scintillators like cerium bromide.

Example case study 2: University of Liverpool, STFC Daresbury Laboratory & Canberra

The University of Liverpool, STFC Daresbury Laboratory and Canberra are working together to commercialise gamma-ray imaging systems with relevance to the Nuclear Decommissioning and Security sectors. Mobile and portable imaging systems are being field trialled as part of funded projects. Support has been secured both from potential end users and through the STFC Innovation Partnership Scheme programme. The same consortium is also driving the technology transfer to enable next generation SPECT (Single Photon Emission Computed Tomography) through the ProSPECTus project.

Example case study 3: University of Manchester & Christie Hospital

The University of Manchester has a well established collaboration with The Christie NHS Foundation Trust, focused on improving the accuracy of Molecular Radiotherapy (MRT) dose calculations. This work provides essential physics input for developing new clinical dosimetry protocols. These protocols are now being routinely used in The Christie nuclear medicine department which treats over 800 MRT patients annually. Support has been provided for this work through the STFC Innovation Partnership and CASE Award schemes. The impact of this research will be further extended beyond the UK with the new MRT Dosimetry project (EMPIR SRT-h18) in which the collaboration will lead work validating dose calculations from simulated and physical 3D printed phantoms. This project will provide a standardised and harmonised European framework for clinical implementation of dose planning in MRT.

Example case study 4: University of Liverpool, STFC Daresbury Laboratory and The Royal Liverpool University Hospital

The Medical Training and Research Laboratory (MTRL) is a joint initiative between the University of Liverpool, the Royal Liverpool University Hospital and STFC Daresbury Laboratory, which delivers hands-on training in medical imaging and develops next generation imaging techniques. The MTRL houses a SPECT/CT scanner that allows students to receive a first-class training experience away from the daily pressures of the hospital environment, where there is often a long wait for access to such in-demand scanning equipment. The facility also allows researchers to test new imaging algorithms and instrumentation systems that are designed to be more efficient and of higher quality for medical diagnosis.

Example Case study 5: University of Glasgow, the National Nuclear Laboratory and Sellafield Ltd.

To interrogate concrete radioactive waste barrels without splitting them apart, the University of Glasgow is developing a system to track cosmic muons as they pass through material volumes that are otherwise opaque to other probes. This allows the imaging of barrel contents, specifically to check whether pieces of uranium fuel have been deposited in intermediate level waste streams. With tens of thousands of such barrels at Sellafield alone requiring appropriate handling there are large potential savings for the decommissioning process.

STFC has also recently supported the creation of a Global Challenge network in “Nuclear Security Science” (NuSec). The network promotes research and technology in Nuclear Security, with an emphasis on radiological detection techniques and systems. The Network is open to all Academic, Industrial and Government scientists and engineers working in Nuclear Security, and acts as a forum to encourage collaboration, networking and capability for all stakeholders.

4.3 Nuclear Physics PhD Education

The biennial UK Postgraduate Nuclear Physics Summer School, which is attended by all UK Nuclear Physics PhD students in the first or second year of their programmes, is an essential part of their PhD training. The school, which has been operating since 1981 has trained in excess of 1000 PhD students. The residential school includes an intense programme of lectures, question and answer sessions, and recreational activities. The School includes the opportunity for every student attendee to give a formal oral presentation about their research work in front of the lecturers and tutors as well as their peers, which provides invaluable experience and formative training.

Recommendation: NPAP recommends STFC continues to support the Postgraduate UK Nuclear Physics Summer School.

With the recognition of the need for high-level training for PhD students covering a broad range of nuclear-physics areas, the UK nuclear-physics community has developed and operated a UK Nuclear Physics Graduate School since 2013. The School, which is presently in its third year of provision, is a collaborative effort involving all of the UK nuclear-physics research groups which provides a voluntary programme of training to all UK nuclear-physics PhD students. The School is organised and managed by academics at the University of the West of Scotland and the University of Manchester, with modules being offered by different groups. To date, eight modules have been offered, and over 40 students have enrolled for the modules. Topics covered include both experimental and theoretical nuclear physics, including a module based on experimental “beam on target” techniques at the Birmingham cyclotron, and a module in nuclear instrumentation offered from state-of-the-art teaching labs at Liverpool. The modules are taught by different methods including face-to-face delivery, distance learning (for example, by video conference), blended learning and residential courses.

The UK’s international leadership in Nuclear Physics coupled with a well-established training network for research students provides a high profile recruitment platform for students. The UK community and STFC should work towards establishing a national framework for the recruitment of international researchers from ODA countries. Establishing a framework for training international research students from countries such as India and China could constitute the first step. Both countries have significant and growing activities in Nuclear Physics research and they possess facilities that would provide complementary benefits to the UK and the ODA country.

Recommendation: The community and STFC should work together to provide assistance to developing countries using ODA funds.

4.4 Industrial Nuclear Data

Industrial nuclear data are those data that underpin the safety and economics of industrial nuclear operations and processes. Stewardship of nuclear data academic grant support is an issue for the community. The community welcomes the recent award of a STFC Global Challenge Network+ in Nuclear Data.

A strong connection between academia, industrial partners, national labs, regulators and UK representatives on international nuclear data committees (IAEA, NEA) is required in order to facilitate the measurement, analysis and dissemination of industrial nuclear data. As identified in a recent submission to the Reactors and Fuels subgroup of the Nuclear Innovations and Reactor Advisory Board (NIRAB) a major issue is the loss of expertise in nuclear data measurement and evaluation within the UK and the prospect of a situation in which the UK will be totally reliant on buying in these skills from abroad, and the associated loss of “top-table” access to groups like the IAEA, NEA and EURATOM.

Three UK universities (Manchester, Surrey and York) have commenced research programmes in industrial nuclear data in response to the EPSRC Fission Energy Call in 2009. This funding has allowed the UK to join the n-TOF collaboration at CERN and create links with the evaluators, industrial partners and national labs. All three Universities have experienced difficulties in securing continued funding. We consider it crucial that the UK identifies funding mechanisms that allow UK nuclear physicists to respond to the nuclear data needs of industry, particularly as new reactor technologies are developed. As a first step towards this, STFC has recently supported a Global Challenge Network Plus in Nuclear Data.

4.5 Outreach, Training, and Education

Beyond satisfying human curiosity around the workings of nature, pure research in nuclear physics has also tremendous societal impact. The community has an excellent track record in public engagement and outreach in a subject that has a natural fascination for many members of the public. Indeed, it fulfills the important role of educating the public in nuclear radiation and its wider aspects, both positive and negative. Nuclear Physicists are frequently invited to share their knowledge and talk about their research at schools, science festivals and community groups. Over 1000 students, teachers and members of the public are engaged through these activities each year. Nuclear Physics is also a key part of the GCSE and A level science curriculum and teachers are always looking for ways to enrich the teaching of nuclear physics in the classroom and often approach our community. The community has responded to this need by running nuclear physics continuing professional development workshops for teachers and masterclasses for students. The teach the “teachers” workshops are supported by the Nuclear Institute and are held in several different locations in June and July. They are always oversubscribed and reach 100 science teachers every year. The masterclasses have been extremely successful (reaching over 250 students in 2015 alone). in enthusing young people to pursue careers in Physics. The Masterclasses are one day events for GCSE or A-level students that focus on the delights of nuclear physics. The events include lectures, laboratory experiments, hand on workshops, careers activities, computer sessions and facility tours. Masterclasses have been run at the Universities of Liverpool, Manchester, Surrey and Birmingham as well as STFC Daresbury Laboratory. Events are supported and organised by the STFC outreach team. Nationally the masterclasses reach over 1500 students pa.

The UK nuclear physics groups such as Manchester, Birmingham (Centre for Nuclear Education and Research), Liverpool and Surrey are 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 recognised outside STFC, e.g. within EPSRC and BIS. The UK Nuclear Physics community provides the following MSc and CPD training:

- Nuclear Science and Technology (NTEC)
- Physics and Technology of Nuclear Reactors
- Radiation Metrology
- Radiation and Environmental Protection

The uptake of this training is typically 160 – 200 MSc students per year with industry CPD at a level of 50 – 60 pa.

5. A STRATEGIC UK NP-STFC PARTNERSHIP

5.1 Update since Previous Roadmap

In 2012, NPAP produced the latest version of the roadmap document, it identified current and future scientific challenges and opportunities for the UK in Nuclear Physics. A set of recommendations for a balanced programme, both in terms of breadth of science and timescale of projects was made. This included both the exploitation phase of existing activities and the longer-term investment in new projects. The 2012 document was used as input to the 2013-14 STFC Programmatic Review, which followed a number of the recommendations.

The general motivation for pursuing Nuclear Physics remains unchanged. There have been a number of important developments since late 2012. Key developments are summarised here:

- (1) Breadth of funded programme: NPAP expressed concern that the lack of breadth in projects in the nuclear physics programme placed the UK in a fragile position. The UK had one funded Nuclear Physics project, NuSTAR, which was developing equipment for the experimental programme at FAIR, GSI, Germany. There was a recommendation that “the UK Nuclear Physics Community requires a balanced programme of projects across the areas of *Hadronic Physics* and *Nuclear Structure and Astrophysics*”. Following the submission of 5 Statements of Interest (SOI), 4 were considered by a Sub-Group of Science Board and 3 (ISOL SRS, JLab Upgrade, ALICE Upgrade) were subsequently invited to submit full proposals and were funded.
- (2) STFC support for University Chair in Nuclear Theory: Nuclear Theory has been strengthened with the start of the third UK theory group at the University of York and the appointment of Prof. J. Dobaczewski and Dr A. Pastore. This is seen by the Community as a clear turning point and the beginning of increased activity in the field.
- (3) Status of FAIR: The UK is now an Associate Membership to FAIR, STFC sits on FAIR Council and has access to the decision making process linked with FAIR. The start-up of FAIR has been delayed, with 2022 the expected date for the startup of the SFRS. Thus, where appropriate, instrumentation constructed through the NuSTAR project is being exploited at other international facilities (e.g. ANL, Cologne, GANIL, Orsay, RIKEN) during the construction phase of FAIR. This ensures maximum scientific return on the investment in the short term.

Internationally both the existing NuPECC (Europe) and new NSAC (USA) long range plans align with the science programme outlined in this document. In the existing Long Range Plan (2010) NuPECC 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.

The strategic plan and associated timescales have been impacted by the significant delay in start up of the FAIR facility. Following the 2015 international review of FAIR the NuSTAR pillar was rated the highest

priority. The UK community has adjusted its strategic planning to fit the modularised start-up of the FAIR facility. The NSAC priorities are exploitation of existing facilities, completion of FRIB and the construction of EIC, which complements the key priorities across the UK nuclear and hadron physics outlined in this document.

As an Associate member of FAIR the UK has been asked, along with the shareholders to provide additional cash funding in proportion with the level of UK membership (0.5%) towards the increased cost of the civil construction of FAIR. The requested UK contribution in 2019 prices is 1.7M€. The UK has no liability to contribute towards the civil construction costs. However, the UK has invested £8M in the construction of components for the NuSTAR experiment. The UK experimental construction project finished in March 2016 and the UK collaboration has plans for testing, commissioning and exploitation of the components at several laboratories before they can be installed at GSI/FAIR.

6. ROADMAP

The UK community is extremely well placed to continue to pursue a world-leading nuclear physics programme, focussed on addressing internationally recognised high-priority science questions. This, however, is only possible through a balanced, diverse and strategic support of key activities.

We **recommend an experimental and theoretical programme** that addresses the high-priority science questions and capitalises on the UK’s world-leading expertise. The programme in the figure below comprises experiments in different project phases, with a balance between physics exploitation, projects, and longer-term R&D. This programme addresses the major questions in the Nuclear and Hadron Physics community. Projects in blue and green represent areas of community interest that are not yet at an approved and funded stage as STFC projects.

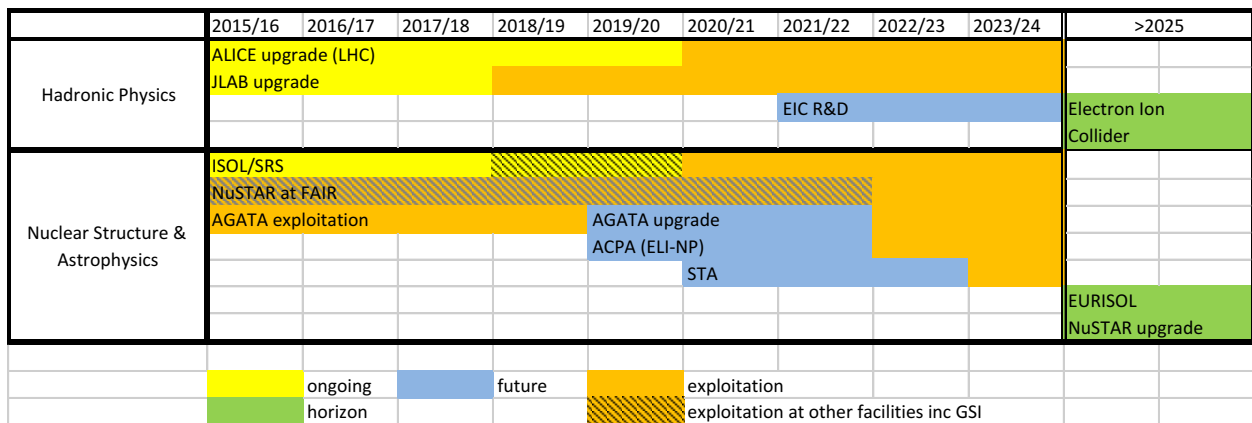


Figure 9: Project timescales