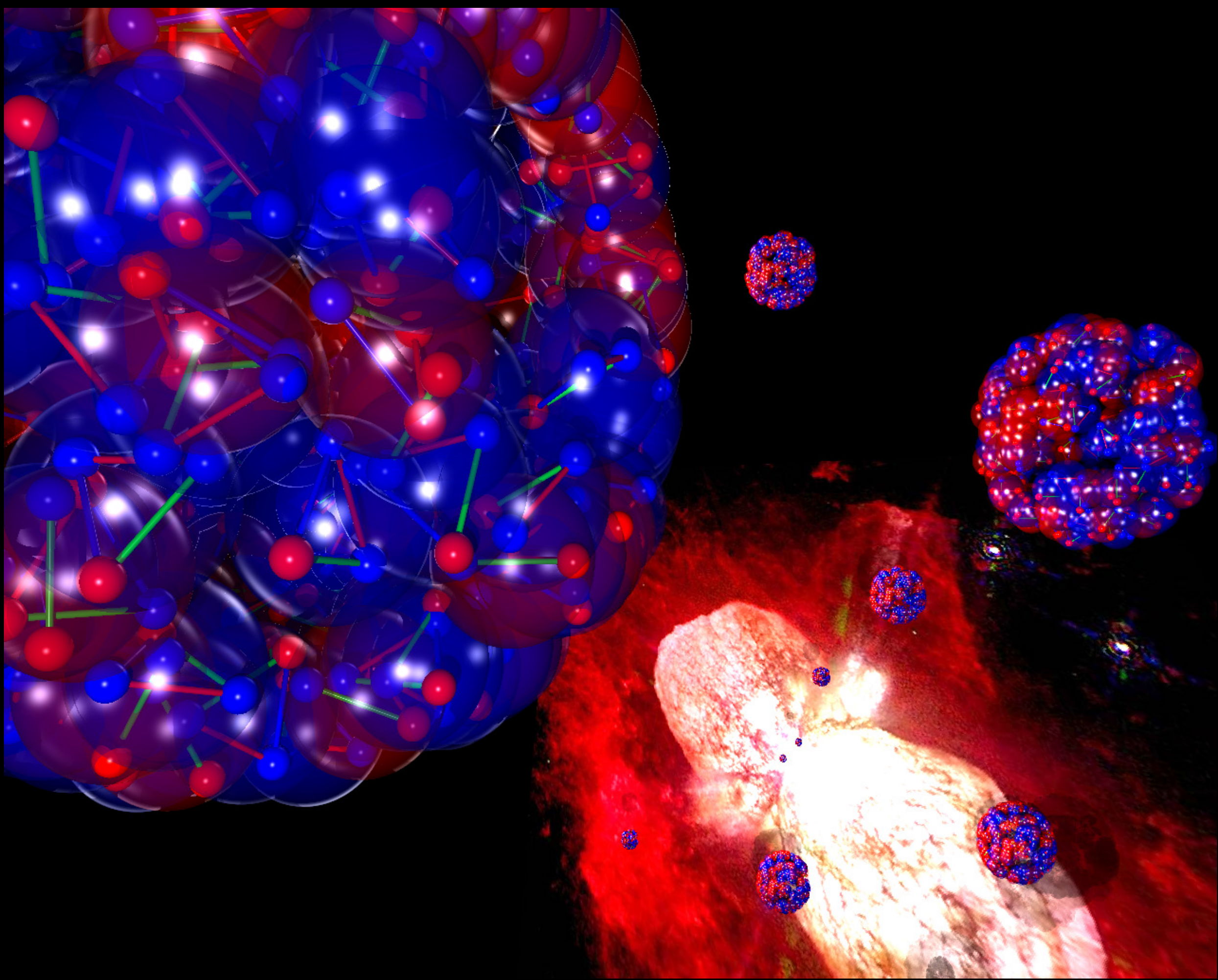
The Physics of Nuclei

Nuclear Matter and

Nucleosynthesis

Report of the Nuclear Physics Advisory Panel updated *June 2018*



UK Nuclear Physics Roadmap 2018

Executive summary

The UK Nuclear Physics community has recognised international leadership and expertise and is a growing and vibrant community of 68 academic staff based at 11 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 (2017) which ranked our community second 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). 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 including the recently observed neutron-star 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 γ-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.

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, **this is on the understanding that FAIR operations and construction costs do not impact further on the future project and exploitation funding for the community.**

The relative size of the UK Nuclear Physics Community means that small changes in funding will have a big impact on the science programme, both in a positive and negative sense. The continuing effects of flat-cash funding cannot be ignored. The outcome of the recent Consolidated Grant round clearly indicates that areas not attracting funding are internationally excellent/world leading. This is damaging the credibility of UK science and impacting an internationally leading science programme.

The advisory panel would like to emphasise the number of supported PDRAs have reached a level too low to properly support the programme as a whole and so the community has had to make very difficult choices. Following recommendations from the previous Balance of Programmes exercise related to the number of PDRA posts supporting the core science programme, no additional money was available, so funding was reallocated from the projects line to support PDRA numbers. Although welcome in the short term, this has had two unfortunately consequences:

- The PDRAs allocated vary in length (are shorter than the CG period) and therefore continuity has been lost in some science themes
- Support for the projects line has been impacted which will have long term negative consequences

The nuclear physics community therefore regard the current level of funding for the whole programme as critically low.

Recommendations:

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

- **The UK should support flagship projects in Nuclear and Hadronic physics** including upgrades that capitalise on previous investments, maximise high-quality science output and UK leadership in international projects. Funding solutions to support capability building within the Nuclear Theory community to support the scientific programme both at a multi institutional and multi-disciplinary level should be investigated.

- **The project research and development (PRD) line should be re-instated** when possible to enable the R&D required to support the next generation of experiments.

- **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.**

- **NPAP recommends STFC support the subscription for access to the future FAIR facility through the international subscription partition.**

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Nuclear Physics Advisory Panel

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1. THE PHYSICS

Overview

Atomic nuclei, consisting of protons and neutrons, make up 99.9% by mass of all visible matter. Despite 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.

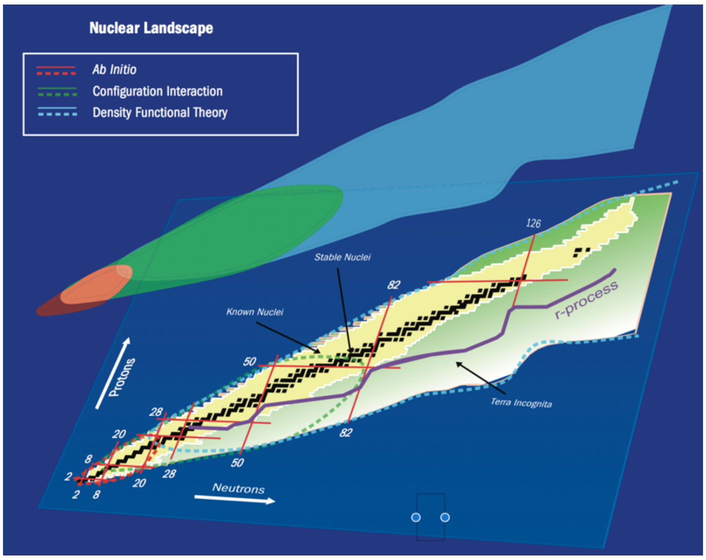

Figure 1: The nuclear landscape showing the strong relationship between experiment and theory

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.

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 the 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?

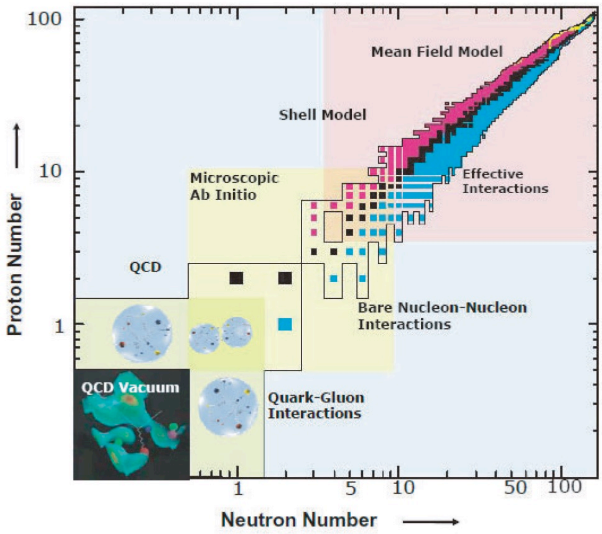

Figure 2: The broad science reach of UK Nuclear Physics

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 second in the world by measure of its field-normalised citation impact. In terms of research volume, the UK is ranked 7th in nuclear physics behind most of the other leading nations. In terms of highly cited papers, the UK is ahead of the other leading scientific nations in nuclear physics. [2017 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 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, their global properties (masses, radii, ground state spins 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. The gravitational-wave observation of a neutron-star merger is a game-changer which observationally demonstrates an r-process site with the required neutron densities. This opens up a new era of r-process nuclear physics, with new questions arising on the role of the nuclear equation of state in the dynamics of the merger and on fission recycling of r-process material.

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, kilonovae, neutron star mergers 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 update. 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 at 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 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-intio* 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 invitations to work with 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 doubly 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~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*≤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}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

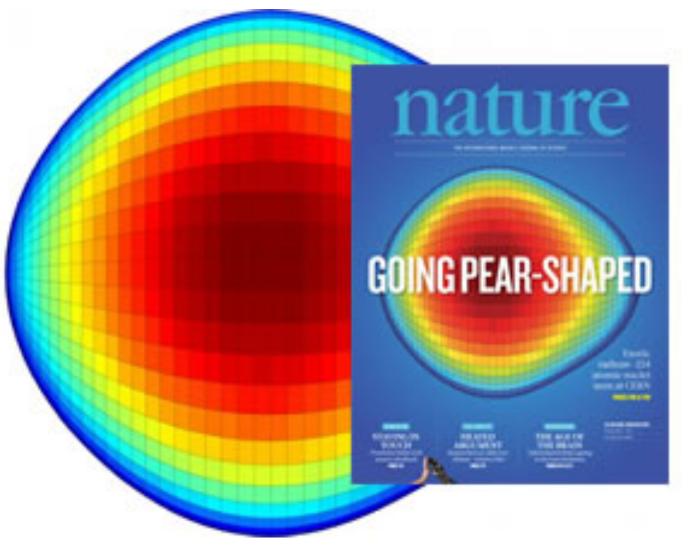

Figure 3: The observation of rigid a octupole (pear-shape) in ^{224}Ra

space. These fundamental 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 an-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 behaviour 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 focused 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 a 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 the 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 $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ reactions to initiate the slow neutron process, and there are many open questions about the different contributions to the rapid neutron-capture process (r-process).

The gravitational-wave observation of a neutron-star merger is a game-changer which observationally demonstrates an r-process site with the required neutron densities. This opens up a new era of r-process nuclear physics, with new questions arising on the role of the nuclear equation of state in the dynamics of the merger and on fission recycling of r-process material. Furthermore, 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: Matter at the Fundamental Scale

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?
- How does the quark and gluon structure of nucleons and nuclei evolve with energy and is there evidence of gluon saturation in high energy nuclear collisions?
- What is the mechanism for confining quarks and gluons in strongly interacting particles?

- What do the spectra of hadrons tell us about the nature of the strong interaction?
- Which exotic hadrons (multi-quark states, hybrid mesons, glue balls) exist and what are their properties?

- 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?
- How do hadron properties relate to large scale structures of matter under extreme conditions, such as neutron stars, black hole formation or matter during the early evolution of the Universe.

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, as a teeming sea of quarks and gluons when illuminated with a high-energy probe and as 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 of the burning questions in the field. 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 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, most notably in the candidate for a charm-pentaquark state and the observation of a hexaquark. Understanding the existence (or absence) of these states presents another way to explore the dynamics of the strong interaction, while the properties of multiquark states have direct implications for the composition of neutron stars and the nuclear equation of state. Hadron resonances are studied by UK nuclear physicists using fixed targets at Jefferson Laboratory (JLab) in the US (CLAS and GlueX collaborations) and at the Mainz Microtron (MAMI) in Germany.

Next generation measurements will allow the spectroscopy of particles containing strange quarks to be detailed for the first time. Such particles may play a crucial role in neutron star physics, and hadronisation following the big bang, and provide unique constraints on QCD, including nucleon structure where the strange nucleon excited states do not overlap. However, creating particles with a high degree of strangeness is difficult using electromagnetic beams which have no intrinsic strangeness. These difficulties can be overcome by exploiting the major advances in electromagnetic beams to enable the first clean and intense strange particle beam facility. In this regard the UK leads a new initiative to develop the K-Long Facility at JLab.

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 the 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 if 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 picture of nucleon structure. Moreover, the functions encoding the spatial and momentum information of the quarks and gluons have recently been related to the pressure distributions inside the nucleon, giving tantalising hints towards the nature of confinement. A vibrant experimental programme is underway in the CLAS, Hall A and Hall C collaborations at JLab, which has recently completed its successful upgrade to double its maximum electron beam energy to 12 GeV. This has opened up a region of phase space that has never previously been accessed and leads 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 and confinement, 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 provided the first tomographic information on the nucleon and given insight to how the properties of nucleons emerge from the non-perturbative nature of QCD. Sensitivity of certain exclusive

processes to the pressure distributions in the nucleon is opening up a new research area on its fundamental gravitational properties.

- 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 first measurements of electroproduction of exotic particles are to give unique constraints on their structure.
- The correlations between nucleons in nuclei have been shown to be predominantly between protons and neutrons, which gives rise to the surprising and counterintuitive consequence that protons, the minority particle species in heavy nuclei, have a higher average momentum 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 extremely high temperature and 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 deconfined, forming a quark-gluon plasma. 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 structure of nuclei. The study of nuclear 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, and 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. It is noteworthy that 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, there is 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. Three-body forces have recently been included in such reactions for the first time. 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~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. Applications of EDF to neutron stars is an active area; recently the effects of non-nucleonic degrees of freedom, including dibaryons, have also been explored. 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, focused 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, and 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 GSI (Germany), 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 EURICA 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, and 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. Prior to the completion of FAIR, experiments will be performed at the existing GSI facility – called FAIR Phase-0 experiments. 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 hadrons 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 hadron 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. This 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 calculations, 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.

The theory community gives the ECT* its strongest possible support, noting also that it is widely used by nuclear experimentalists and by theorists and experimentalists from other parts of the STFC community, and that it enables fruitful dialogue between all of these constituencies. A series of workshops is organised each year covering a wide range of nuclear physics topics with an emphasis on theory. The UK has taken leadership on organising a number of workshops. **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 hadron spectroscopy and scattering experiments
- Fast tracking and particle identification detectors
- Trigger and slow control systems
- High-Performance Computing (HPC) centres

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 complementary 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 programmes, studying the most neutron- and proton-rich nuclei (up to Z≤60-66). Deep-inelastic reactions are planned to study neutron-rich N~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 provided state-of-the-art techniques and detectors to make step changes in sensitivity. At the University of Jyväskylä, 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 Jyväskylä 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 (0νββ matrix elements) which will allow the absolute mass of the neutrino to be determined if 0νββ 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 uA 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 requires high-energy hadron beams, particularly of heavy nuclei. 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. The 12 GeV JLab upgrade has been very successfully completed in 2017 and experiments are currently on-going in all four of its experimental halls.

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 has enabled UK groups to make a significant impact in the science programme at the upgraded facility, capitalising on leadership roles in the current and 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. Likewise, UK physicists are leading research into exotic states of strongly-interacting matter with the GLUEX detector in Hall D and their leadership in the proposed K-Long facility, which will see the construction of a strange particle beam-line for Hall D. 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 programmes 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 (AIDA detectors and electronics) will be deployed at GSI in 2018 (FAIR-0 experiments).

- 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.
- 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 9 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 conveners 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 main goal of the **ISOL-SRS project** is to build two spectrometers for precision measurements of charged particles emitted in nuclear reactions induced by radioactive ion beams. One spectrometer, the ISOLDE Solenoidal Spectrometer (ISS), is based on the novel helical orbital spectrometer concept and will take radioactive beams from HIE-ISOLDE at CERN. The other spectrometer will be operated within the ultra high vacuum (UHV) of the CRYRING low-energy storage ring at FAIR. Fast, chemistry-independent, radioactive ion beam spills separated in-flight by the Fragment Recoil Separator (FRS) will be stacked, cooled and decelerated by the Experimental Storage Ring (ESR) and then transferred to the CRYRING where they will re-circulate and interact with a pure gas target. Both spectrometers will employ high granularity silicon-detector systems with ASIC-based readout that will enable the reaction products to be studied with unsurpassed energy resolution and sensitivity.

Figure 4a: Setting up detector and target systems inside the ISS magnet in preparation for in-beam tests at ISOLDE, CERN.

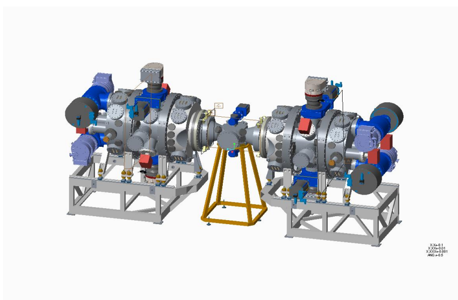

Figure 4b: Upstream and downstream UHV vacuum chambers for CRYRING with gas jet interaction chamber at the centre.

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: 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 GSI, and performing experiments at the world's leading radioactive-ion beam 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, nuclear structure, transfer reactions, and Coulomb excitation.

Technological Expertise/Drivers/Impact: Key advances will stem from the development of silicon detectors capable of operating in the UHV environment of storage rings. The development of the ISS 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. Both spectrometers will utilize UK leadership in state of the art nuclear instrumentation and data acquisition systems.

Institutions: 8. Academics: 32   Project value: £3.3M

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 focused 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.

- 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 (2019): 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 20 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.
- 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.
- FAIR (2025): Next generation European Fragmentation facility at GSI. Campaigns of experiments as part of the NuSTAR collaboration using HISPEC, DESPEC and R3B.

3.1.4 Future Projects (near-term)

The DRACULA project: The UK will lead the design, construction and implementation of a new, state-of-the-art charged-particle detection system for use at the next generation, world-leading radioactive beams facility FRIB. This advanced silicon array, which represents the UK's contribution to FRIB, will provide unrivalled opportunities for measuring key properties of rare isotopes relevant for astrophysical processes and shell structure evolution. Moreover, information obtained with DRACULA at the frontiers of nuclear stability could provide the means to instigate a new era for shell model and reaction theory in the UK.
Institutions: 5. Academics: 14 Estimated project value: £3.7M

Advance charged-particle array at ELI-NP (ACPA@ELI): Advanced charged-particle array at ELI-NP (ACPA@ELI): The ELI-NP Gamma-Beam System (GBS) includes the EU-funded electron accelerator built at STFC Daresbury Laboratory under contract with INFN. The first UK-led commissioning experiment with charged-particle detection is planned for the 2019 GBS commissioning phase, with the full GBS commissioned 2020. In addition to the ACPA@ELI project (currently an accepted SOI), there is scope for UK nuclear physics lead in other experiments and UK-detector technology for the GBS, including gamma-fluorescence and gamma-induced neutron emission, as well as in the ISOL facility under development at the GBS facility (ISOL demonstrator funded).
Institutions: 6. Academics: 12 Estimated project value: £1.4M

AGATA upgrade: AGATA is a major European project to develop, build and operate a world-leading precision gamma-ray detection instrument for in-beam studies of nuclei. The completion of AGATA is one of the highlight recommendations in the NuPECC LRP. The objective of this project is for the UK to contribute at the highest level to the current and planned phases of AGATA through (a) purchase of AGATA equipment, including detectors (which enables the UK to meet its obligations under the current Memorandum of Understanding) and (b) to utilise the UK's leading technical and scientific capabilities to push the development of AGATA towards the new science opportunities provided by the future facilities such as SPES and FAIR.
Institutions: 6. Academics: 20 Estimated project value: £3.5M

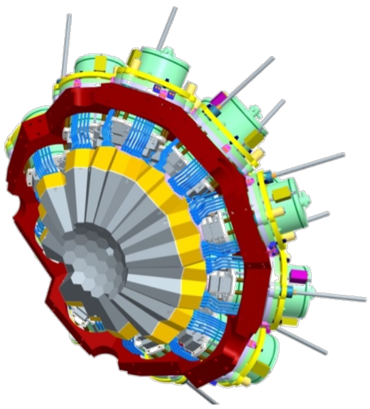

Figure 5: Schematic diagram of the AGATA spectrometer

3.1.5 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. R&D is required to establish the position sensitivity within the scintillators and then to investigate an engineering solution. It is likely project research and development (PRD) funding will be required prior to a full project proposal.

Instrumentation@Jyväskylä: Over the past 25 years, the UK has built a strong and productive programme of research at the University of Jyväskylä Accelerator Laboratory in Finland, particularly in the areas of gamma-ray spectroscopy and laser spectroscopy of exotic nuclei. Through EPSRC and STFC funding, UK physicists have been instrumental in the development of equipment such as GREAT, SAGE, LISA, and laser-spectroscopy set-up at IGISOL. A new opportunity has recently been identified using the new MARA vacuum-filled recoil separator which will allow the UK programme to be strengthened and extended: the MARA Low Energy Branch (LEB) will deliver low-energy beams of mass-separated ions that will be used for decay, laser, and mass spectroscopy on dedicated beamlines. The MARA-LEB project is presently at conceptual stage; once the concept is proven, the UK will request funds from STFC to build new equipment and establish UK leadership for some areas of the MARA-LEB project.

3.1.6 Future Projects (Horizon)

NuSTAR upgrade: FAIR will be the European flagship facility for the coming decades. The unique accelerator and experimental facilities will allow for a large variety of unprecedented fore-front research in physics and applied science. The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale, deepening our understanding of fundamental questions. The UK is associate member of FAIR. FAIR is expected to deliver its first beams in around 2025. It will produce intense, high brilliance beams of all chemical elements up to uranium with energies in the range E~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 for NUSTAR and AIDA will be will be deployed at GSI in 2018 (FAIR-0 experiments). Based on this and other experience of operating these detectors at a range of international facilities such as RIKEN, GANIL, Orsay, Argonne and Jyväskylä, along with future developments in detector technology and electronics, a NUSTAR upgrade project is envisaged in the future. This will likely include support for the DEGAS Germanium array, Schottky pickup detectors for the storage ring and MAPS (DMAPS) detectors.

EURISOL: The ultimate ISOL facility in Europe will be EURISOL for which an extensive R&D program and a design study have been carried out in the last decade. It consists of a superconducting linear accelerator providing 1 GeV protons with a power of 5 MW, but also capable of accelerating deuterons, ^{3}He and ions up to mass 40. The beams will impinge simultaneously on two types of targets, either directly or after neutron production, through a spallation target surrounded by kilograms of fissile material. The unstable nuclei produced diffuse out of the target, are ionised and selected, and can be used directly at low energy or reaccelerated by another linear accelerator to energies up to 150 MeV per nucleon in order to induce nuclear reactions. As an intermediate step, the EURISOL DF project aims at integrating the ongoing efforts and developments at the intermediate major ISOL facilities of HIE-ISOLDE, SPES and SPIRAL2, the planned ISOL@MYRRHA facility, and the existing JYFL and ALTO facilities. EURISOL DF will use the synergies and complementarities between the various facilities to build a programme to bridge the technological gap between present facilities and EURISOL.

3.1.7 Cyclotron & National User facility

The University of Birmingham Nuclear Physics group is proposing an upgrade of the Birmingham MC40 cyclotron with an external electron cyclotron resonance (ECR) source to dramatically increase the variety of ion beams available and therefore increase the breadth of the nuclear physics programme. This would be part of the development of a national user facility when combined with other current accelerator infrastructure renewal proposals. This upgrade proposal takes a phased approach.

Phase 1: 2018-2019: Will include a feasibility study together with an external specialist such as IBA, to investigate how to adapt the Birmingham MC40 machine from using its current internal ion source for light ion beams (H, He, N etc.) to an external ion-ECR source capable of producing ions of most elements. The ECR source itself is a prototype of the Jyväskylä ion source and is being sought at essentially no cost through a decommissioning project overseas.

Phase 2: 2019-2021: Subject to the outcome of the feasibility study the ion source modifications would be implemented. In addition, this time scale is consistent with concurrent plans for an infrastructure development with the materials and high-energy communities. Through the National Nuclear User Facility (NNUF) a new low-energy high-current (<100 mA) proton and deuteron machine for neutron damage studies etc. has been proposed to BEIS. This is ranked highly by NNUF and awaiting funding having been endorsed at a national level in the applications community. This would mean neutron fluences of up to 10^{13} n/s (significantly higher than foreseen at NFS) which could be used by the nuclear physics community for the study of neutron-rich nuclei, e.g. approaching the r-process path. This would complement the cyclotron upgrade proposed here by making additional space available for cyclotron beam-lines and associated experimental apparatus.

3.2 Hadron Physics

3.2.1 Involvement and Leadership

UK Involvement:
13 Academics at 6 Institutions (Birmingham, Derby, Edinburgh (York), 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.

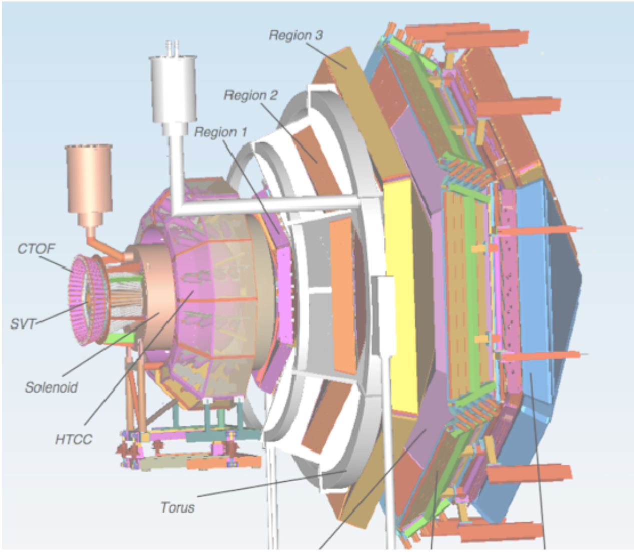

Figure 6: A schematic diagram of the CLAS12 detector

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 (multiquark 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

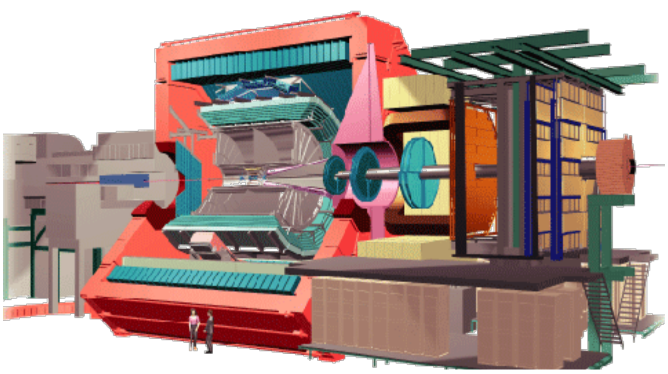
Figure 7: The ALICE experiment

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.

The JLAB2 project will include key developments to deliver the world's most intense and clean neutral kaon beam (Klong@JLAB). The project will also enable UK groups to lead R&D for the next major project in the field, the $1Bn electron-ion collider. Klong@JLAB aims to discover over 50 currently elusive particles within a 2 year measurement to improve our understanding of the nucleon and QCD. It is supported by 60 institutions & 200 physicists from the Europe, US and China. The UK will contribute the Kaon Flux Monitoring apparatus, which is key to the physics aims of the proposal.
Institutions: 2 Academics: 7   *Estimated project value: £2M*

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 EIC R&D: 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 and very high luminosity, 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, leading to an extensive R&D programme in tracking and particle identification detectors and trigger systems from 2020 onwards. Some of this work has already started with external funding and the opportunity would greatly benefit from Project research and development support (PRD) once CD0 approval has been received in the US.
Institutions: 6 Academics: 13   *Estimated project value: £2.5M*

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 is planned to be a high-energy polarised 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 2027-2032. The EIC is currently undergoing a review by the National Academy of Sciences, with a favourable response expected later this year. The first step in the approval process is for the facility to achieve Critical Decision Zero (CD0) status, establishing mission need, which may follow within months after the Academy review.

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 and Projects

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 has concentrated on three main activities over the years 2015 to 2018:

- Training of students on advanced theoretical topics, with one TALENT school hosted and more planned.
- A visitor programme has attracted 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 are 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.

Neutrino-nucleus interactions project: The UK theory groups have expertise both in nuclear structure and in reactions, including using modern ab-initio methods and effective field theory. This technology can be harnessed to calculate experimentally-crucial cross-sections with greater precision and sophistication than most currently-used codes. Additional expertise in nuclear structure and chiral physics would also contribute, and synergy with the UK particle experimental program is envisaged. An investment of roughly £0.5M funding for workforce and £0.4M for computer power would be required.

Theoretical studies of spontaneous and induced fission project: A proposal to develop a leadership hub for theoretical studies of spontaneous and induced fission. This will build upon expertise in self-consistent methods, building synergic connections with experimental studies. Newton fellowship funding to support PDRAs is being sought along with an ERC-AdG proposal for 0.5MEuro/year funding for manpower and 1MEuro funding for computer power.

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 programme. This will be aided by 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. There is also a case to be made for the employment of staff dedicated to theoretical support for experimental programmes, along the lines of cross-community posts.

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, maximise high-quality science output and UK leadership in international projects. Funding solutions to support capability building within the Nuclear Theory community to support the scientific programme both at a multi institutional and multi-disciplinary level should be investigated.

4. UK NUCLEAR PHYSICS STANDING AND IMPACT

4.1 The UK Nuclear Physics Community Makeup

The nuclear physics research community in the UK comprises of 68 academic staff at 11 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 second in the world by measure of its impact and citations, STFC IMPACT Report 2017. The performance of the UK community is shown in table 1.

Nuclear physics	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Number of publications	347	296	489	496	476	393	520
UK position	7	7	7	7	7	7	7
Citation Impact (CI)	6.74	13	16	15.4			
UK position	2	2	1	1			
Normalised Citation Impact (NCI)	1.62	1.72	5.12	3.1	2.6	1.8	1.6
UK position	2	2	1	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

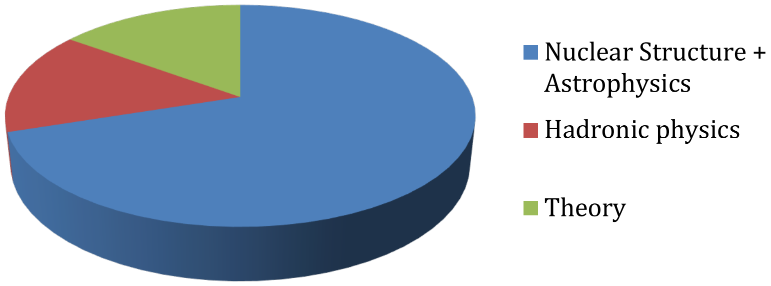

Figure 8: Theme areas studied by academic staff

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.

4.2 Key technologies and technology development

The UK Nuclear Physics community has world leading expertise in the development of state-of-the-art instrumentation. The recognised international strength of our instrumentation and innovation personnel that support both the science and impact programme are essential to this success. A summary of the key technologies and capabilities required to enable the future science programme:

- Germanium detector fabrication, repair, characterisation and long term support.
- Miniaturisation of discrete readout electronics (JFET based PAs) for germanium detectors. CMOS readout. Germanium ASIC and associated mounting of the digital processing chain on the detector.

- Online correction of differential non-linearity for energy resolution applications
- MAPS (DMAPS)
- Photo-sensors with sub-picosecond timing resolution
- Position sensitive scintillators based on SiPM technology

Key engineering and design support is required to support this programme both centrally (STFC) and at the Universities where appropriate. There is an ongoing shortage of skilled technical effort to provide professional support across the breadth of the nuclear physics programme. At an institutional level that has resulted in a significant reduction in the level of technical support and an increasing reliance on the good will of Universities to maintain this at a reduced level.

4.3 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 MRTDosimetry 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.

4.4 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.

4.5 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 supported a Global Challenge Network Plus in Nuclear Data.

4.6 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 GSCE 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.

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
- Nuclear Decommissioning and Waste Management
- 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.

4.7 GCRF and ICSF engagement opportunities

The UK Nuclear Physics community believe there are significant opportunities for engagement with the GCRF and ISCF funding streams. Broadly speaking the community is unclear how best to engage in the first instance in an effective and meaningful way. The STFC GCRF initiatives to "pump prime" potential projects are therefore positively received.

One example was the STFC Global Challenges Research Fund (2017) which funded a workshop on Advanced Nuclear Science and Technology Techniques (ANSTT) at iThemba Labs (Cape Town) 5-9 March 2018. The focus of the workshop was to build capacity and collaboration between UK and African scientists and between those in South Africa, Botswana, Tanzania, Zambia and Nigeria. Following this a number of research collaborations have developed which will lead to future opportunities in both applied research, training and fast timing gamma-ray measurements. Separately, initiatives with India are also developing with a focus on the Nuclear Astrophysics programme.

There are clear potential opportunities with the International Atomic Energy Authority (IAEA). The IAEA is contributing to the achievement of the UN Sustainable Development Goals by helping countries to use nuclear and isotopic techniques to address in areas such as ending hunger; health and well-being; water and sanitation; energy; industry, innovation and infrastructure; climate change; and sustainability.

The STFC Nuclear community has key capability in nuclear education, training and research and has strong relationships with the IAEA, which could have potential for GCRF research and training. STFC funded university groups work in collaboration with the IAEA to accredit MSc level nuclear technology courses, have capability in nuclear education, training and research and have proposed collaborations, in the first instance, with South Africa but with the potential to be expanded elsewhere.

NPAP would like to emphasise that such funding is not a replacement for core funding of the science programme.

5. ROADMAP

5.1 Proposed Roadmap

The UK community is extremely well placed to continue to pursue a world-leading nuclear physics programme, focused 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 or R+D.

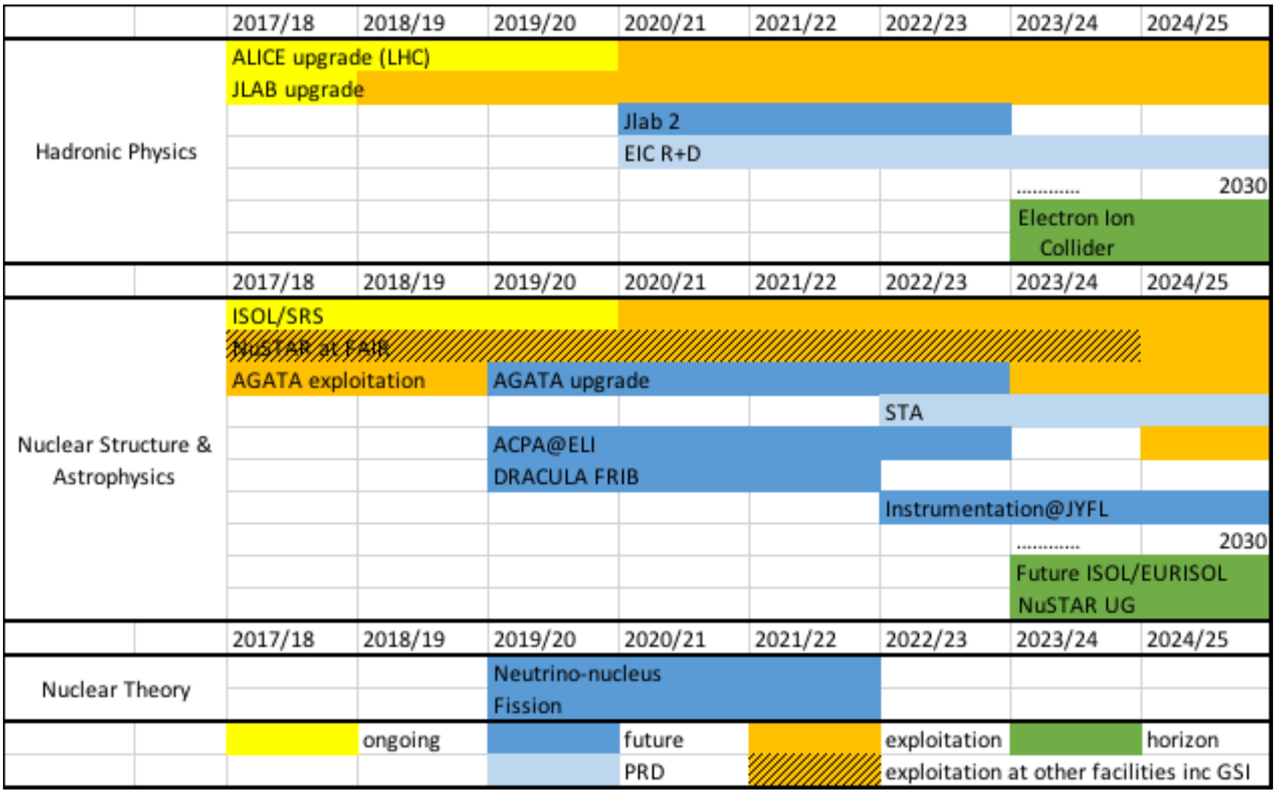

Figure 9: Project timescales

Internationally both the existing NuPECC (Europe) and NSAC (USA) long range plans align with the science programme outlined in this document. In the new NuPECC Long Range Plan (2017) NuPECC set its priorities for nuclear structure and astrophysics. The key recommendations are:

- Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM,NUSTAR and PANDA.
- Support for construction, augmentation and exploitation of world leading ISOL facilities in Europe.
- Support for the full exploitation of existing and emerging facilities
- Support for ALICE and the heavy-ion programme at the LHC with the planned experimental upgrades.
- Support to the completion of AGATA in full geometry

The NSAC priories 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.

The UK is an Associate Membership of 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 2025 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.

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. Other than the delays to construction this is in recognition that the scope of FAIR has changed with UK loosing involvement in PANDA and LASPEC, but gaining involvement in the ring internal spectrometer CRYING through the ISOL-SRS project. The UK community remains broadly supportive of FAIR, although the current programme of research at is GSI is limited, the future programme will benefit greatly from FAIR.

Going forward the community would recommend access is funded through the international subscription partition.

Recommendation: NPAP recommends STFC support the subscription for access to the future FAIR facility through the international subscription partition.

5.2 Enabling the Roadmap

The relative size of the UK Nuclear Physics Community means that small changes in funding will have a big impact on the science programme, both in a positive and negative sense. The continuing effects of flat-cash funding cannot be ignored. The outcome of the recent Consolidated Grant round clearly indicates that areas not attracting funding are internationally excellent/world leading. This is damaging the credibility of UK science and impacting an internationally leading science programme.

The advisory panel would like to emphasise the number of supported PDRAs have reached a level too low to properly support the programme as a whole and so the community has had to make very difficult choices. Following recommendations from the previous Balance of Programmes exercise related to the number of PDRA posts supporting the core science programme, no additional money was available, so funding was reallocated from the projects line to support PDRA numbers. Although welcome in the short term, this has had two unfortunately consequences:

- The PDRAs allocated vary in length (are shorter than the CG period) and therefore continuity has been lost in some science themes
- Support for the projects line has been impacted which will have long term negative consequences

The nuclear physics community therefore regard the current level of funding for the whole programme as critically low.

The UK should support flagship projects in Nuclear and Hadronic physics including upgrades that capitalise on previous investments, maximise high-quality science output and UK leadership in international projects. Funding solutions to support capability building within the Nuclear Theory community to enable the scientific programme both at a multi institutional and multi-disciplinary level should be investigated.

The development of the new instrumentation technologies that will enable the future science programme requires an appropriate funding mechanism. The Project research and development (PRD) line (or similar) should be re-instated when possible to enable the R&D required to support the next generation of experiments.

There is a general consensus that UK leadership in a number of key technical areas is a risk in the longer term. This includes mechanical design, electronic engineers, detector specialists etc. For example, in the period 2025-2030 the UK expects to play a leading role in the development of the trigger system for a future EIC detector. There is a concern over the continuity of support for key technical staff in the current flat cash funding scenario. Failure to adequately support these posts will ultimately erode the UK's ability to maintain areas of established technical leadership.

Key engineering and design support is required to support this programme both centrally (STFC) and at the Universities where appropriate. There is an ongoing shortage of skilled technical effort to provide professional support across the breadth of the nuclear physics programme. At an institutional level that has resulted in a significant reduction in the level of technical support and an increasing reliance on the good will of Universities to maintain this at a reduced level.