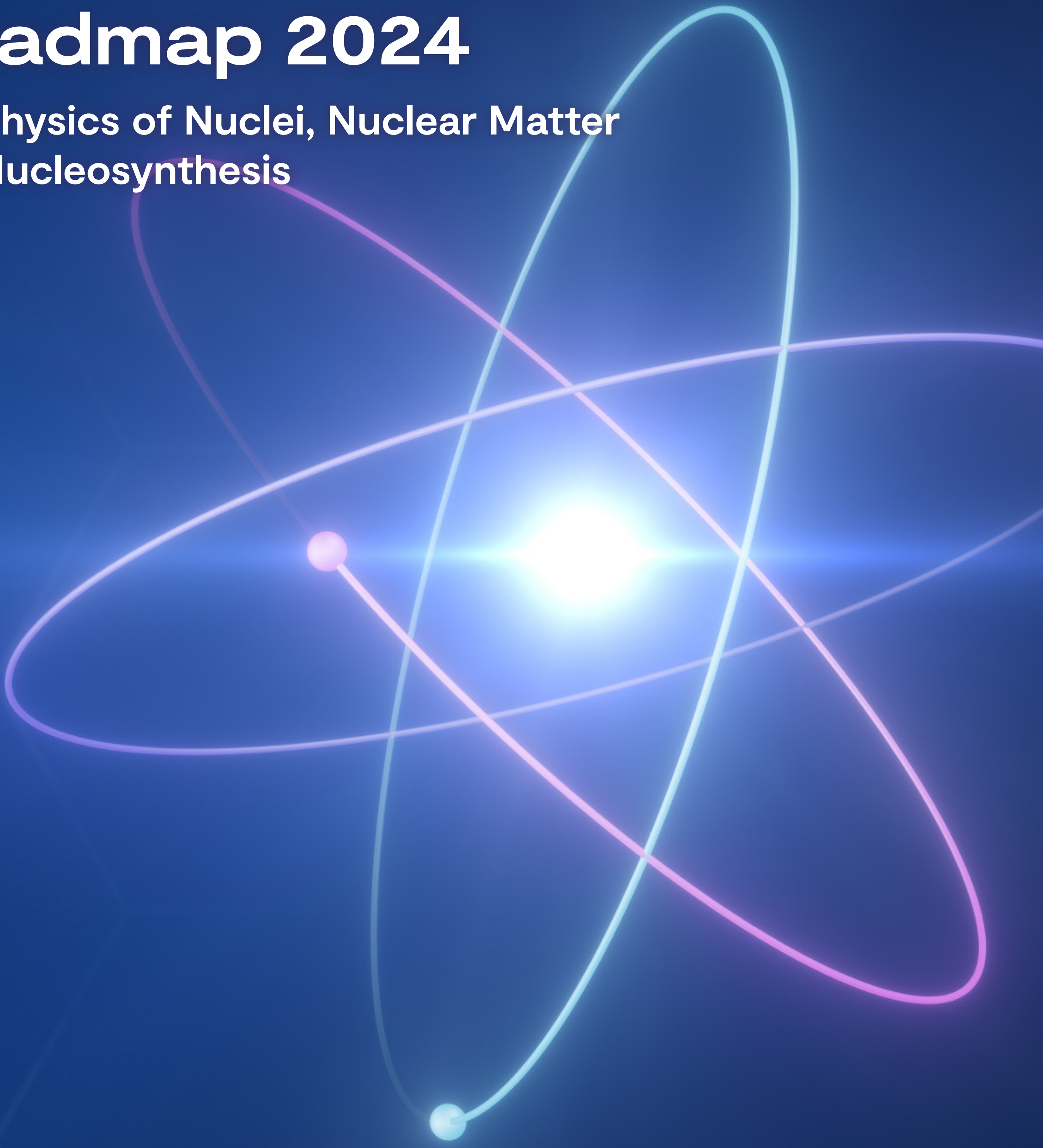
Science and
Technology
Facilities Council

UK Nuclear Physics Roadmap 2024

The Physics of Nuclei, Nuclear Matter and Nucleosynthesis



Nuclear Physics Roadmap 2024

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List of acronyms and abbreviations:

AGB: Asymptotic Giant Branch stars

AI: Artificial Intelligence

ALPIDE: ALICE Pixel Detector

ASIC: Application-Specific Integrated Circuit

BBN: Big Bang Nucleosynthesis

BB: BigBite Spectrometer

C: Charge Conjugation

CC: Cross Community

CFFs: Compton Form Factors

CMOS MAPS: Complementary Metal-Oxide-Semiconductor Monolithic Active Pixel Sensors

DAQ: Data Acquisition system

DIS: Deep Inelastic Scattering

DVCS: Deeply Virtual Compton Scattering

EDI: Equality, Diversity and Inclusion

EDM: Electric Dipole Moment

EMP: Extremely Metal Poor (stars)

EoS: nuclear Equation of State

ERC: European Research Council

GPDs: Generalised parton distribution functions

HPC: High Performance Computing

i-process: intermediate neutron-capture process

IOP: Institute Of Physics

ISOL: Isotope-separation online

LRP: Long Range Plan

ML: Machine Learning

MR-TOF-MS: Multi-Reflection Time-Of-Flight Mass-Spectrometer

NDBD: Neutrinoless Double β Decay

NEDFs: Nuclear Energy Density Functionals

NPGP: Nuclear Physics Grants Panel

NSAC: Nuclear Science Advisory Committee

NuPECC: Nuclear Physics European Collaboration Committee

p-process: proton-capture process

P: Parity

PID: Particle IDentification

PDRA: Post-Doctoral Research Associate

PET: Positron Emission Tomography

PPAN: Particle Physics, Astronomy and Nuclear Physics

QCD: Quantum ChromoDynamics

QGP: Quark-Qluon Plasma

QT: Quantum Technologies

r- process: rapid neutron-capture process

rp-process: rapid proton-capture process

s-process: slow neutron-capture process

SBS: Super Bigbite Spectrometer

SHE: SuperHeavy Elements

SIDIS: Semi-Inclusive Deep Inelastic Scattering

STEM: Science, Technology, Engineering and Maths

T: Time Reversal

TCS: Time-like Compton Scattering

TDIS: Tagged Deep Inelastic Scattering

TPC: Time-Projection Chamber

Executive summary

The UK Nuclear Physics community consists of 84 academic staff and fellows at 13 institutions working on fundamental nuclear physics and addressing questions concerning the structure and reactions of exotic nuclei, nuclear astrophysical processes from quiescent stars to neutron-star mergers, and how the strong force characterises hadrons and hot, dense nuclear matter. The key fundamental science questions driving this endeavour are:

i. How does the strong force acting within nuclear matter determine the structure of atomic nuclei?
ii. How do nuclear reactions generate energy and nucleosynthesis in astrophysical sites?
iii. How do the properties of hadrons arise and what is the nature of the quark-gluon plasma?

In parallel, the community has embraced the impact agenda with work in areas of applied nuclear physics. Examples of fundamental and applied work can be found later in this document.

By international standards, the UK community is modest in size and focussed on two areas: hadron physics and nuclear structure & astrophysics. Concentration of effort and resources allows the community to punch above its weight and enables an internationally leading science programme, state-of-the-art instrument development, and leading positions for UK scientists in international collaborations. It is therefore critical for the health of the community to maintain leadership in both areas.

The consolidated grant funding is essential to on-going scientific work, to exploiting previous investments and to seed new opportunities. Preserving and, indeed, growing exploitation activity supported by the consolidated grant line is the overwhelming priority of the community. Continuing the growth in PDRA positions secured in the last grants round is important since they are vital to support exploitation and the skills pipeline.

Experimental work is done predominantly at overseas accelerator laboratories, such as JLab, CERN, FRIB, FAIR, TRIUMF, JYFL, GANIL, and RIKEN. Beam time for individual experiments is secured by UK spokespeople in the face of strong international competition. Access to such world-class hadron, electron, neutron, and ion-beam facilities is critical to the success of the community. It is vital to be able to harness the distinct benefits of radioactive beams produced by both fragmentation (FAIR, FRIB, RIKEN) and isotope-separation online (ISOLDE-CERN, TRIUMF), supplemented by work with stable ions. Hadron physics programmes exploit relativistic heavy-ion beams at ALICE-CERN and electrons at JLab, and the community is ensuring opportunities presented by the EIC can be realised in the future.

Leading roles in large international projects provide essential buy-in to facilities and collaborations. The UK has a strong record, supported by recent UKRI investments such as upgrades to JLab detectors, AGATA, the ISOLDE Solenoidal Spectrometer, FAUST at FRIB, HYPATIA at RIKEN, contributions to HISPEC/DESPEC and R^{3}B at

FAIR, and detectors for EIC. As part of the ten-year planning exercise, the community discussed many ideas for future projects in fundamental areas. A prioritised plan is proposed as part of this document, but it must be realised that new ideas will emerge during the next decade. To maintain the community's health and diversity, it will be important to balance investment across hadron physics and nuclear structure & astrophysics. Projects looking for support from the PPRP line are detailed and prioritised in Section 8.

As part of the process of community engagement and 10-year plan, several very large and ambitious ideas were presented. These would be considered out of reach of current PPAN budgets, or are sufficiently large to perturb the diversity and health of the community. They are presented as aspirational, showing the potential for additional investment beyond current budgets.

The UK community is perhaps unique amongst most developed countries in having few theorists; fractions of theorists in the US and in most European and Asian countries are significantly larger. It is a community priority to seek ways to address this issue without jeopardising the success of the current programme or its diversity. There is a strong community desire to engage with STFC to find ways to grow UK nuclear theory in an effective, efficient and sustainable way. Moreover, it is important for the UK to have sovereign capability in nuclear theory to underpin the nuclear data needed for industry and there is potential to leverage additional support in this context.

The support pipeline in terms of skills and technology is critical for the future of nuclear physics in two ways.

Firstly, the studentship and fellowship programmes, along with PDRAs funded through the consolidated grant, have proved to be essential for the flow of talented individuals into the discipline. Without maintaining these to at least the current level, the future of nuclear physics in the UK would be significantly undermined. Clearly, there are benefits to an expansion, should funds become available. While STFC studentships feed the academic discipline, they also provide trained researchers with nuclear skills and expertise for a wide range of industries including nuclear energy, medicine and security.

Secondly, on the technical side, early R&D funding streams are vital to develop and de-risk novel approaches ready for implementation in future projects. These opportunities should encompass equipment development and novel computational approaches for theoretical studies.

It is notable that nuclear physics is successful in senior fellowship programmes beyond STFC (university schemes, Royal Society, UKRI and other sources) and individuals within the community have secured ERC awards at all levels (starter, consolidator and advanced grants). These different styles of funding complement STFC funding vehicles.

The skills and expertise, developed over many decades in fundamental physics, places the community in a unique position to make significant contributions to applied nuclear physics. This provides underpinning academic capacity to serve the UK’s needs in trace element analysis, critical data for fission and fusion energy, decommissioning, security applications and medical therapy, imaging and dosimetry. The UK community has enthusiastically engaged with the increasing importance of the impact agenda, in parallel to and closely linked with fundamental nuclear physics. It is difficult (and unhelpful) to separate too much the fundamental and applied work of the community. Indeed, the community has expressly wished to present applied activities alongside fundamental work, even though the stakeholders reach well beyond STFC.

The portfolio of applied work is a broad church, involving collaboration with many allied fields. It is on a variety of different scales, from small project work to initiation of new major facilities, such as the High-Flux Accelerator-Driven Neutron Source at Birmingham. Resource is drawn from a wide range of funders, including STFC innovations, university impact/knowledge transfer resources, EPSRC, Innovate UK and industry funding. Research partners comprise industry, charities and other organisations, such as NPL, NHS, NNL, NDA and AWE.

Applied work is often explicitly interdisciplinary, cross-council, or even beyond UKRI, making progress more challenging than for projects solely within the remit of one research council. The community has ambitious ideas for consolidating and enhancing such work via centres of excellence or new facilities that serve both fundamental and applied science. These are also presented within this document, as it is the hope of the community that STFC might act as a champion to help bridge cross-council gaps, weave UKRI partnerships and source funding to address societal challenges using expertise gained from fundamental science.

Allied to this impact arena, the community continues to have an excellent record of accomplishment in public engagement and outreach in a subject that has a natural fascination for many members of the public, particularly helping younger people to be attracted into science in general.

High-Level Recommendations:

The UK Nuclear Physics community should be supported to continue to pursue world-leading experimental and theoretical nuclear physics programmes focused on high-priority science questions; STFC consolidated-grant and pipeline funding for skills and technology are critical to future success.

STFC should support international projects in nuclear and hadronic physics that may capitalise on previous investments via upgrades or seize new opportunities, and that maximise high-quality science output and UK leadership.

Novel funding solutions should be found to support capacity building within nuclear theory to support the fundamental science and “UK PLC” needs.

Early R&D and responsive-mode support should be enhanced to enable and to de-risk novel technology required to support the next generation of experiments and theoretical initiatives, whilst also allowing the community to be more agile in responding to emerging opportunities.

STFC should assist the community in furthering experimental and theoretical efforts in applied nuclear physics, acting as a champion to help bridge cross council gaps, weave UKRI partnerships and source funding to address societal challenges using expertise gained from fundamental science and to maintain sovereign capability for the UK in the nuclear area.

10-Year Plan Recommendations:

The nuclear physics community has conducted an in-depth 10-year-plan analysis, presented in Chapter 8 of the Roadmap, and prioritised projects within two groups. Group A aims to maintain and expand the support of the novel, vibrant and exciting physics goals proposed within the core programme. Group B aims to make a quantum leap towards initiatives that break away from the confines of the existing core programme and respond to the identified burning needs and opportunities. The summary table of all proposals is available below.

Within group A, two Top-Priority proposals have been identified in the domain of nuclear structure and astrophysics:

1) Low-energy physics at the limits of stability, which aims to develop the capability to perform complete spectroscopy on the most exotic isotopes available in the near future at worldwide facilities
2) TRISTAN@ISOLDE, which will enable access to a broader range of direct reactions for the study of nuclear structure in exotic nuclei at CERN, whilst also providing access to reactions of astrophysical interest. This will be accomplished through the development of bespoke detection systems

and a Top-Priority proposal has been identified in the domain of Hadron Physics:

> JLab Future, to cement and grow UK leadership in exploitation of the current ongoing 12GeV era programme, and also realise new scientific leadership opportunities for potential future JLab facility upgrades, to further science outputs in hadron structure and spectroscopy. This will also be essential to maintain scientific leadership in hadron physics on route to the EIC.

Within group B, three specific Top-Priority aspirational proposals have been identified:

1) Nuclear Theory Centre, which aims to respond to the existential threat related to the inadequate level of resources available to the theoretical activity and expertise in the UK
2) Nuclear Astrophysics Centre, which would bring the UK research in nuclear astrophysics to the unprecedented level of activity commensurate with the existing potential
3) New experimental facility for Accelerated Beams for Research and Applications (ABRA), which would constitute a unique experimental research centre on the British Isles and equip the UK nuclear physics community with internationally competitive infrastructure

and a Top-Priority proposal in the domain of Hadron Physics has been identified:

> Leveraging the UK's unique technological expertise in CMOS MAPs trackers would enable the UK to play a leading role in the construction of ALICE 3, to study the properties of the quark-gluon plasma with heavy ion beams at CERN.

1. Physics

1.1 Overarching physics goals

Nuclear structure & reactions

The ultimate goal of nuclear physics is a quantitative, all-encompassing description of atomic nuclei that is grounded in QCD and electroweak theory. Nuclear physics contributes to endeavours to understand many-body fermionic systems, which remains a fantastic challenge for modern science. In the field of nuclear structure and reaction physics the challenge of studying these quantum systems leads to a number of open questions:

- Where are the limits of nuclear existence?
- How does nuclear structure evolve in exotic nuclear systems?
- How well are nuclei described in terms of the underlying fundamental interactions based on QCD?
- What are the mechanisms that drive the emergence of new structural phenomena in exotic nuclei?
- What are the physical properties that govern nuclear reactions?

To answer these questions requires the study of nuclei towards the extremes of neutron/proton asymmetry. Indeed, the study of exotic nuclei, away from the small subset of nuclei that are stable, has resulted in the discovery of deviations from established nuclear structure such as changes in the magic numbers corresponding to closed shells in the nuclear shell model, perceived weakening of the separation between spin-orbit partners, and unexpected limits of binding energy. These phenomena elucidate the importance of different components of the nucleon-nucleon interaction, the impact of finite binding in weakly bound systems and the importance of three-body forces.

Describing the atomic nucleus in terms of single particles orbiting in a mean-field potential is a cornerstone of our understanding of the nucleus. Experimental investigations of masses, radii and energies of excited states have pointed to changes in shell structure. In light to medium mass nuclei, for example, the N=20 shell closure disappears with a new one emerging at the drip line in ^{24}O at N=16. Shell closures at N=32 and 34 also emerge in Ca isotopes. Spectroscopic tools such as transfer or knockout reactions have enabled studies of the single-particle properties of nuclei across the nuclear chart, probing the evolution of shell-model orbitals. The evolution of these shell closures can be explained in terms of the interplay between different components, central/spin-orbit/tensor, of the neutron-proton interaction. Phenomena have emerged in nuclei that have been attributed to a weakening of the spin-orbit interaction due to changes in nuclear density at the nuclear surface or central density depletions – a so-called bubble nucleus. Effects due to the weakly bound nature of exotic nuclei are also important in describing the evolution of shell-model orbitals and offer another explanation. Doubly magic nuclei offer exceptional testing grounds for the nuclear shell model and provide robust constraints for nuclear theory. Experimental efforts to probe single-particle properties around ^{100}Sn and ^{132}Sn remain a driver for the development of radioactive beams at ISOL and fragmentation facilities. Shell closures provide enhanced stability in nuclei and the search for new shell closures, including deformed ones, is the subject of superheavy-element studies, which seek to locate an island of stability in superheavy nuclei.

Nuclear shapes naturally emerge because of nuclear interactions, with wide variation (prolate, oblate, octupole). In fact, different nuclear shapes can even exist within the same nuclear system, and so are not just dependent on the mass or ground-state properties of the system but rather the wave function of the individual states. There are many regions of the nuclear chart where shape coexistence is prevalent or where sudden onset of deformation occurs. The sudden onset around A=100 has features of a quantum phase transition. Octupole deformed nuclei, where nuclei have a pear shape, provide systems where permanent electric dipole moments (EDM) could be found, with effects due to an EDM enhancement in molecular systems. Detailed spectroscopic studies using Coulomb excitation, γ and electron spectroscopy, and laser spectroscopy are needed to both characterise deformation and probe new physics.

Understanding the limits of nuclear existence provides stringent tests of nuclear models and impacts the production of the chemical elements in stellar environments. Conversely, the temperature of stellar environments could influence the nuclear drip lines. Studies of nuclei at the drip line, and how they decay through processes such as proton emission provides information of the ground-state wave function of the most exotic nuclei. For example, the location of the drip line in oxygen isotopes has highlighted the need to include three-body forces in nuclear models to reproduce the location of the drip line.

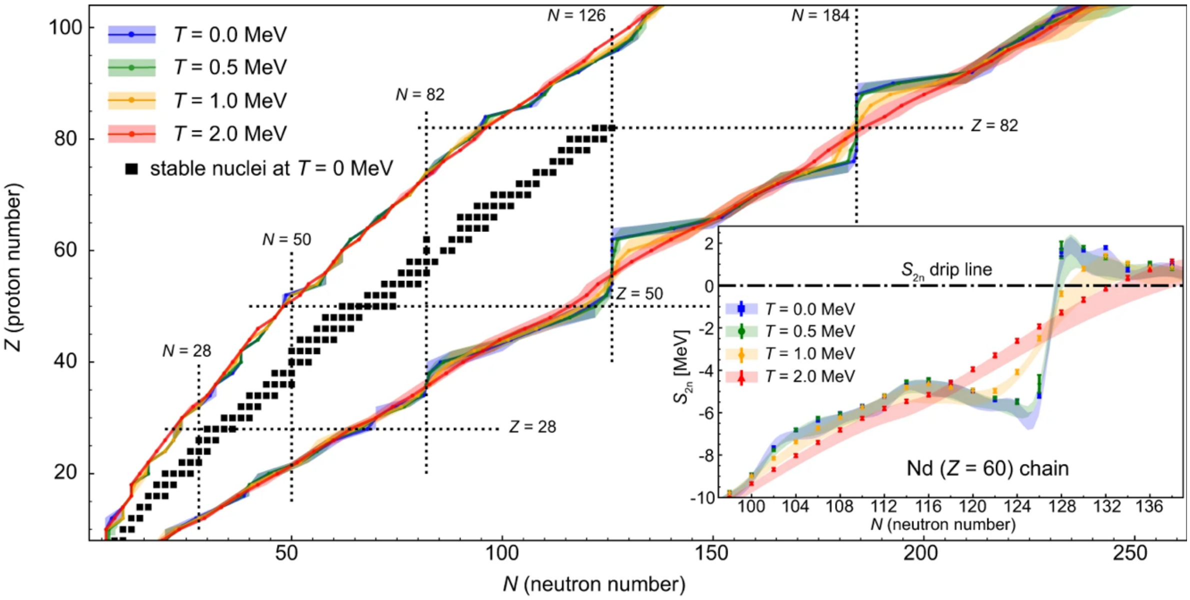

Figure 1: Two-nucleon drip lines at finite temperature. Reproduced with permission from A. Ravlić *et al.*, Nature Comm. 14 4834 (2023)

The theoretical description of the atomic nucleus remains a challenge, with a true form of the nuclear interaction not fully defined and the ability to obtain the quantum mechanical solutions for the many-body problem challenging. The most state-of-the-art models use either realistic or effective interactions or energy density functionals, which are increasingly more accurate, informed by comparison to data across broad ranges of the nuclear chart. Functionals are becoming more closely related or rooted to fundamental interactions in QCD via the effective chiral field theory.

The UK nuclear physics community is leading experimental and theoretical work in probing, and understanding, nuclear structure away from stability towards and at the limits of nuclear existence. It leads studies in both the single-particle properties of exotic nuclei and collective structures along with probing the ground-state properties of nuclei to the drip lines, which is complemented by theoretical developments in effective and ab-initio theory. This is demonstrated through roles as spokespersons of international collaborations and conveners of experimental set-ups as well as membership in the programme advisory committees at international facilities. UK leadership in mean-field, ab-initio and reaction theory has resulted in significant collaboration between UK theory and international experimental collaborations to interpret measurements in exotic nuclei. The UK community remains a leader in the development of novel technologies that are deployed at international facilities to allow us to answer key questions in nuclear structure physics.

Nuclear astrophysics

Remarkable recent advances in astronomical observations and analyses of meteoritic samples have provided us with unprecedented insight into stellar nucleosynthesis, the properties of exploding stars and neutron star mergers, and other celestial phenomena. These scenarios are responsible for the rich diversity of chemical elements we find in our galaxy, and the resulting distribution of matter is expected to play a key role in the habitability of planetary systems. Yet, despite the wealth of available observational data, our understanding of many key stages of stellar nucleosynthesis remains elusive because of large uncertainties in the underlying nuclear processes that govern the evolution of extreme stellar environments throughout the cosmos. By exploring microscopic information on the structure and reaction properties of key atomic nuclei, the field of nuclear astrophysics endeavours to unravel mysteries surrounding the origin of chemical elements and the generation of energy across the Universe. Key questions in nuclear astrophysics include:

- How did first generation stars evolve and die?
- What is the origin of heavy elements in our galaxy?
- What are the nuclear processes that drive explosive stellar phenomena, such as novae, supernovae, X-ray bursts and neutron star mergers?
- How do radioisotopes inform models of stellar explosions and planetary-system formation?
- How do nuclear reactions govern the evolution of massive stars?
- How do nuclear reactions affect the abundance of short-lived radioactivity in planetary systems?
- What are the nucleosynthetic processes that determine the abundance distribution of elements in the Universe?

Nuclear Astrophysics in the UK is a highly vibrant and dynamic research area, with dedicated groups focussed on understanding stellar evolution and nucleosynthesis. Studies of the structure and reaction properties of unstable nuclei are essential, as it is these nuclei that determine both the pathway of nucleosynthesis and the rate of energy release in explosive astronomical events. Over the past few decades, tremendous strides have been made in the development of radioactive ion beam technology, which now allow us to experimentally investigate such nuclei in the laboratory. It is now possible to directly access astrophysical reactions involved in the proton-capture (p-), rapid proton-capture (rp-), intermediate neutron-capture (i-) and weak rapid neutron-capture (r-) processes, as well as those affecting cosmic-ray emission and non-solar isotopic abundances in pre-solar grains.

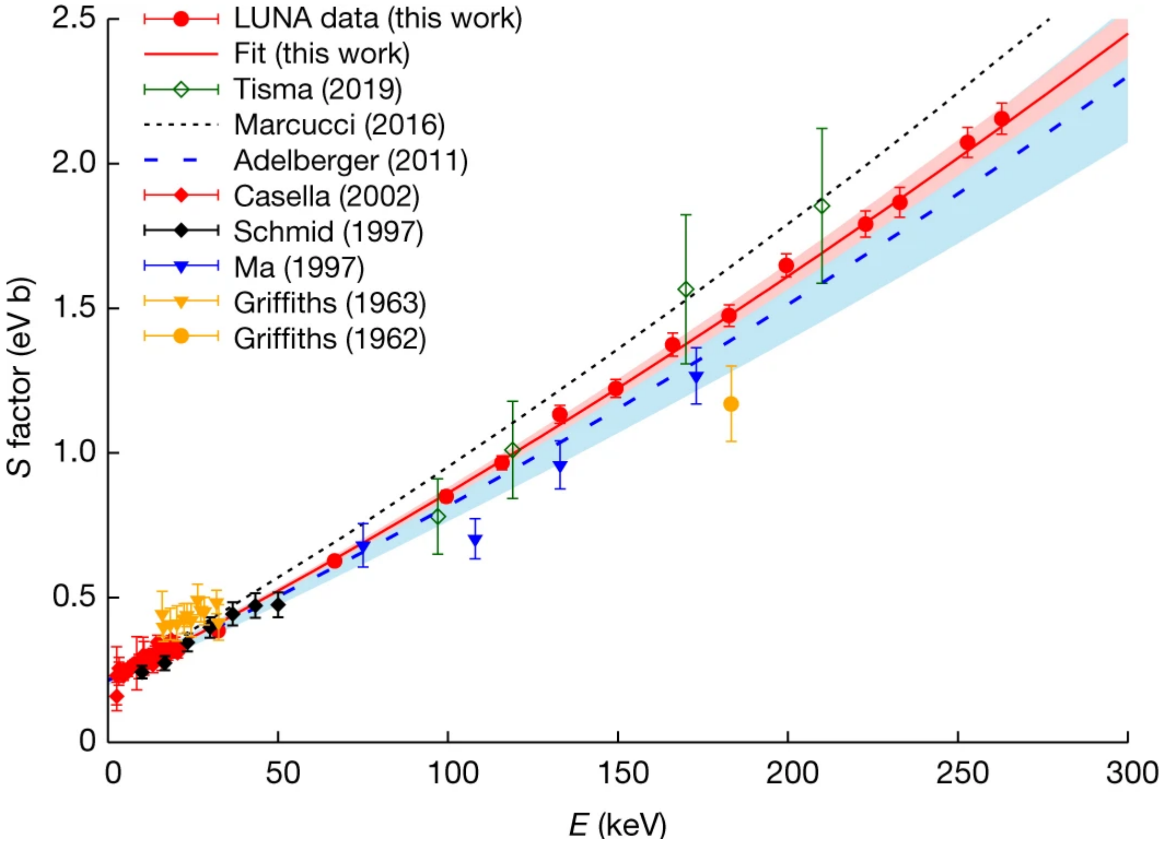

Figure 2: At BBN energies (Ecm ≈ 30−300 keV), the new LUNA results (filled red circles, with total (statistical + systematic) error bars) indicate a faster deuterium destruction compared with a best fit (blue dashed line) of previous experimental data, but a slower destruction compared with theoretical calculations (black dotted line). Reproduced with permission from V. Mossa *et al.*, Nature **587**, 210 (2020).

Alongside explosive nucleosynthesis, many open questions remain for quiescent burning environments, such as main sequence stars and Asymptotic Giant Branch (AGB) stars. These scenarios operate at lower temperatures and pressures than those of novae or supernovae, and, hence, the corresponding reaction rates are very small for the nuclear processes involved. This makes the direct measurement of such reactions extremely challenging. However, the advent of cutting-edge underground accelerator facilities, such as LUNA, has led to pioneering new measurements in a low-background environment, allowing us to measure reaction cross-sections at the lowest energy frontiers, often for the first time. UK scientists are also at the forefront of neutron-capture cross-section studies on heavy nuclei. These measurements are key to predict slow neutron-capture (s-) abundances, which can be used to calculate galactic chemical evolution, test stellar models against observations, and determine r-process abundance patterns. Experimental activities are performed at world-leading facilities, such as n_TOF (CERN) and others, often involving the development of novel detection systems. Finally, heavy ion storage rings such as ESR and CRYING at GSI have recently opened exciting new avenues for pioneering measurements of radiative capture cross sections on radioactive nuclei as they exploit unique capabilities of stored and recirculated beams aimed at overcoming beam intensity limitations at traditional Radioactive Ion Beam facilities.

Looking ahead, major breakthroughs in nuclear astrophysics will need to maximise the latest developments in nuclear accelerator technologies (e.g. FRIB, ARIEL, HIE-ISOLDE, underground facilities, storage rings, neutron beams), astronomical observables from modern telescopes (e.g. JWST, ELT, Fermi, LIGO) and astrophysical modelling (e.g. 3D). Specifically, closer ties are needed between the nuclear experiment, nuclear theory, astronomy, astrophysics, and particle astrophysics communities. The incorporation of experimental data and theoretical estimates of nuclear properties (e.g. masses and decay rates for heavy element nucleosynthesis) in advanced stellar models is vital to interpret complex observations accurately for an understanding of the evolution of chemical elements. Interdisciplinary initiatives such as the UK BRIDGCE network have provided an important first step in establishing a link between these fields. However, targeted support for enabling such activities is clearly needed, and a more focused interdisciplinary research centre could supply the desired endorsement necessary to combine UK expertise on key issues in nuclear astrophysics.

Hadron Physics

Hadron physics is concerned with the study of the underlying structure and interactions of nuclear matter at its most fundamental partonic level, i.e. 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 seeks to address are as follows:

- What is the structure of hadrons in terms of their most fundamental constituents?
- How do phenomena such as confinement and the origins of the nucleon mass and spin emerge from the dynamics of QCD?
- How does the quark and gluon structure of hadrons evolve with energy, and is there evidence of gluon saturation in high-energy nuclear collisions?
- What do the spectra of hadrons tell us about the nature of the strong interaction?
- Which exotic hadrons exist and what are their properties?
- What are the phases of strongly interacting matter, what is the nature of the quark-gluon plasma, and how does it emerge from fundamental interactions?

> How do hadron and nuclear 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 the bound states of QCD which make up almost all 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 constituent (or dressed) valence quarks when studied with a low-energy probe, and as a sea of quarks and gluons when studied with a high-energy probe, and a range of manifestations in-between. The properties of hadrons, such as their mass and spin, are a direct consequence of their complicated internal dynamics, which is still not entirely understood. For example, it is known that the Higgs-generated mass of light quarks comprises only roughly 1% of the nucleon mass. Likewise, 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 that 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 made significant progress. Nevertheless, the field remains largely phenomenological, and theoretical advances require guidance from experiments performed across the widest possible range of energy scales on the key hadronic and nuclear systems, and employing 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 excited 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 new “exotic” particles. Hadron spectroscopy is an invaluable tool to study QCD in the non-perturbative regime and allows us to obtain an insight of the origin of confinement and the role gluonic excitations play in the formation of mesons and baryons. Study of the spectra, combining novel experimental tools as well as partial-wave analyses, allows us to map out how quarks interact in forming hadronic states. From QCD-inspired models beyond the baseline quark picture, hadrons have been built with additional quarks and antiquarks, gluonic excitations, and states of pure gluons. The expectation is that if it is possible to construct such states via the strong interaction, then they should appear in particle interactions in a similar manner to standard quark model hadrons and be measurable. 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.

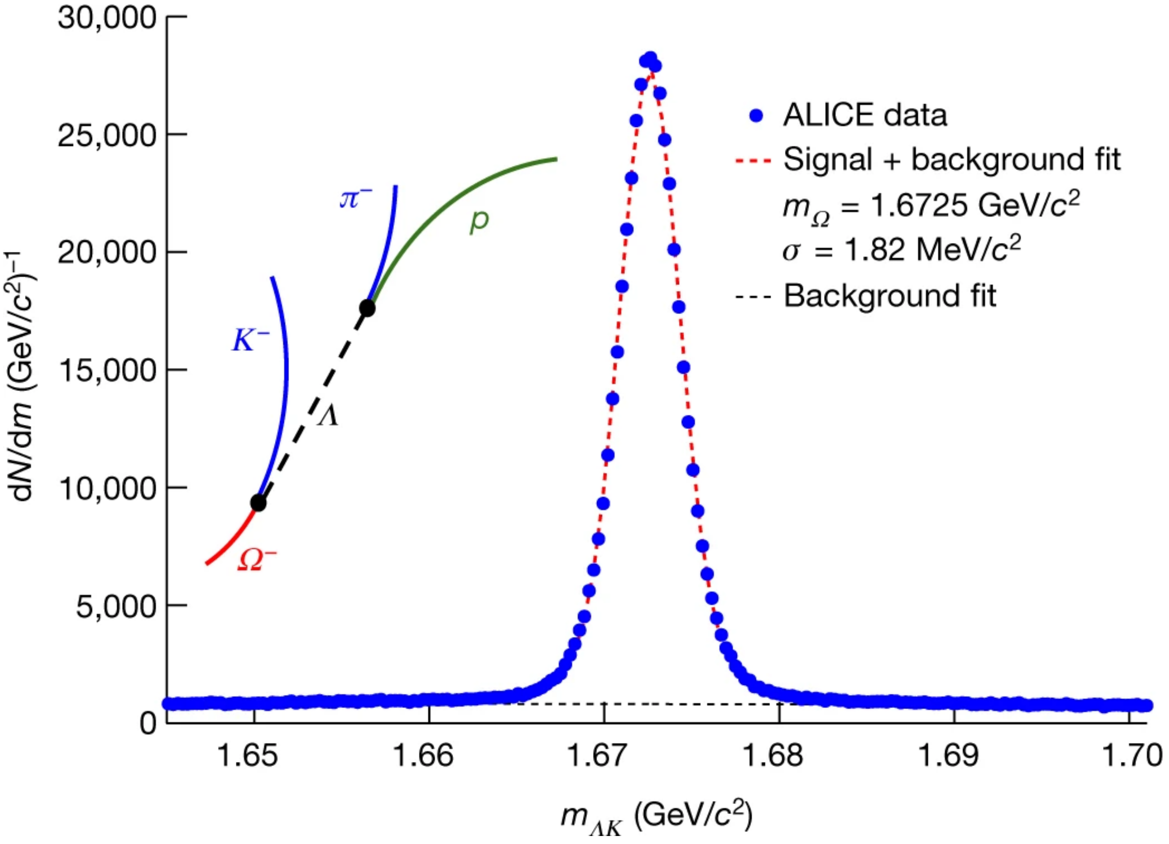

Figure 3: Sketch of the weak decay of Ω^- into a Λ and a K^-, and measured invariant mass distribution (blue points) of ΛK^- and combinations. The dotted red line represents the fit to the data including signal and background, and the black dotted line the background alone. Reproduced with permission from ALICE Collaboration, Nature 588, 232 (2020).

The field of hadron structure is also essential to elucidate information on the key questions above and is studied via fixed-target lepton-nucleon/nuclei scattering experiments by the UK community. For example, the nucleon can be probed in elastic collisions, where electrons are scattered from the charge distributions inside it. This can yield information about the size and shape of the nucleon and its quark density, illuminating the differences between protons and neutrons. UK physicists also use a variety of deep inelastic scattering (DIS) reactions. Using electron beams at high energies, it is possible to transfer so much momentum to the target nucleon that other particles are “knocked” out of it — for example, mesons or high-energy photons — or the target particle may completely fragment into a number of newly-formed hadrons. These reactions allow for tomography studies: the scattering in these interactions happens directly from the constituents inside the nucleon, telling us about its internal dynamics and helping us to build up a multidimensional picture of nucleon structure. For example, one key tool to obtaining this 3D picture are the generalised parton distribution functions (GPDs), which encode the spatial and momentum information of the quarks and gluons, and can shed light, directly, on the partonic orbital angular momentum contribution to hadron spin. GPDs have also recently been related to the pressure distributions and shear forces inside the nucleon, giving tantalising hints towards the nature of confinement.

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. Nuclear collisions at 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 (QGP). 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. This deconfined state provides an ideal laboratory for the understanding of QCD. A large number of measurements of azimuthal anisotropy in Pb-Pb collisions for different particles, show strong collective effects of the produced particles. Together with the suppression of high momentum particles, this gives a clear picture of the collision: the QGP evolves by expanding over time, pulling particles with it, while fast particles are slowed down. Comparing the bulk of thermalized particle production with calculation, the QGP evolution is very well described by relativistic hydrodynamics of an almost perfect liquid expanding at around 0.7c. This suggests that the QGP still contains substantial interactions between its constituents. While there is no substantial suppression of high-momentum particles, there are clear indications of collective effects in p-Pb and pp collisions as well. This is surprising as within the timescale of these collisions no thermalisation or QGP formation is expected.

Measurements of light hadrons tell us about the collective expansion of the system, while hard probes like jets and heavy flavour quarks can tell us about the transport properties of the medium. Measurements of photons and dilepton pairs give an insight into the earlier states of the evolution. In this way, QCD can be studied in a system with quarks and gluons as the relevant degrees of freedom. Comparing measurements in heavy-ion collisions with those in high- and low-multiplicity proton-proton or proton-nucleus collisions gives important information about the transition from hadronic interactions to the production of the QGP.

The abundant production of many different hadron states also allows for measurements of their properties and interactions. 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.

1.2 Achievements, highlights & discoveries

Since the 2019 NPAP Roadmap, the UK Nuclear Physics community has consistently been present at the forefront of many important advances in this research area.

Selected time-ordered highlights from the vibrant Nuclear Physics research programme in the period 2020-2024 are:

The role of the underlying single-particle structure for the Pygmy Dipole Resonance was established Phys. Rev. Lett. **125**, 102503 (2020).

Improved cross-sections of the deuterium burning D(p,γ)^{3}He reaction led to BBN estimates of the baryon density at the 1.6 percent level, in excellent agreement with a recent analysis of the cosmic microwave background Nature **587**, 210 (2020).

Measuring correlations in the momentum space between hadron pairs, produced in ultra-relativistic proton–proton collisions at the CERN Large Hadron Collider (LHC), provided a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons Nature **588**, 232 (2020).

The spin polarization of the recoiling neutron in deuterium photodisintegration was measured. The results could be related to the excitation of the d*(2380) hexaquark Phys. Rev. Lett. **124**, 132001 (2020).

High-precision measurements of states above threshold in ^{34}Ar have constrained the astrophysically important ^{33}Cl(p,γ)^{34}Ar reaction, decisive in identifying the origins of pre-solar grains Phys. Rev. Lett. **124**, 252702 (2020).

The first ab initio calculations of radii and charge densities for open-shell nuclei beyond Sn have been made, comparing well to experiment and paving the way for ab initio studies of exotic charge density distributions at the limit of the present ab initio mass domain Phys. Rev. Lett. **125**, 182501 (2020).

The first a-priori lattice QCD calculation showing the presence of a hadron resonance with an exotic combination of spin, parity and charge conjugation quantum numbers was performed Phys. Rev. D **103**, 054502 (2021).

The first mass measurements of neutron-deficient Yb isotopes at TITAN, TRIUMF, established the existence of the N=82 neutron shell up to the proton drip line. Further, the detection and mass measurement of ^{150}Yb marked the first ever discovery of an isotope at TRIUMF Phys. Rev. Lett. **127**, 112501 (2021).

The predicted quantum entanglement in linear polarisation for annihilation γ photons was proposed as a method to quantify and remove the unwanted backgrounds in Positron Emission Tomography (PET) Nature Communications **12**, 2646 (2021).

Joint mass measurements at TRIUMF and NSCL/FRIB investigate the evolution of the exotic N=32 and 34 neutron shell closures in combination with state-of-the-art ab initio calculations Phys. Rev. Lett. **126**, 042501 (2021).

New Λ-N scattering data was obtained from an experiment performed at CEBAF utilising the Large Acceptance Spectrometer (CLAS) detector to study the Λp→Λp elastic scattering cross section in the incident Λ momentum range 0.9–2.0 GeV/c Phys. Rev. Lett. **127**, 272302 (2021).

A first ever measurement of timelike Compton scattering, which provides a way to test the universality of the generalized parton distributions, has been made with the CLAS12 detector at JLab Phys. Rev. Lett. **127**, 262501 (2021).

ALICE confirmed the dead-cone effect, an important prediction from perturbative QCD. Careful measurements using charmed quarks as partons show that small-angle radiative splittings in jet evolution are suppressed for larger parton masses Nature **605**, 440 (2022).

Highlights from the nucleon tomography programme at JLab include a first experimental extraction of all four helicity-conserving Compton form factors (CFFs) of the nucleon as a function of Bjorken x with extremely high precision Phys Rev. Lett. **128**, 252002 (2022), as well as a first CLAS12 measurement of deeply virtual Compton scattering beam-spin asymmetries in the extended valence region Phys. Rev. Lett. **130**, 211902 (2023).

Measurements performed at the Triangle Universities Nuclear Laboratory were interpreted in the chiral effective field theory framework to extract the electromagnetic dipole polarizabilities of the proton Phys. Rev. Lett. **128,** 132502 (2022).

A resonance-like structure near threshold in the four-neutron system that is consistent with a quasi-bound tetraneutron state existing for a very short time was observed Nature **606**, 678 (2022).

First mass measurements of neutron-rich Cr isotopes established the summit of the N=40 island of inversion Phys. Lett. B **833**, 137288 (2022).

An abrupt change in the indium nuclear dipole moment at N=82 was observed. Together with the accompanying theoretical findings, it led to an understanding of how seemingly simple single-particle phenomena naturally emerge from complex interactions among protons and neutrons Nature **607**, 260 (2022).

Recent results from two-nucleon knockout reactions in inclusive elastic electron scattering from ^{3}H and ^{3}He mirror nuclei have yielded new insights on the pairing of nucleons inside the nucleus Nature **609**, 41 (2022).

Simultaneous γ-ray and electron spectroscopy demonstrated a step-up in experimental sensitivity and paves the way for systematic studies of electric monopole transitions in this region Communications Physics **5**, 213 (2022).

Nucleon drip lines were determined using several relativistic energy density functionals with different underlying interactions, demonstrating considerable alterations of the neutron drip line with temperature increase, especially near the magic numbers Nature Comm. **14**, 4834 (2023).

A new technique for determining fission barriers was demonstrated that will open the way for the study of fission properties with short-lived nuclear species Phys. Rev. Lett. **130**, 202501 (2023).

Direct mass measurements of neutron-deficient nuclides at GSI closing on ^{100}Sn Phys. Lett. B **839**, 137833 (2023).

ALICE measured the hypertriton ${}^{3}_{\Lambda}\mathrm{H}$ lifetime and Λ separation energy, solving a puzzle as their values previously seemed inconsistent with models of the particle Phys. Rev. Lett. **131**, 102302 (2023).

Measurements of the vibronic structure of radium monofluoride molecules were reported, which demonstrated an improvement in resolution of more than two orders of magnitude compared to the state of the art Nature Physics **20**, 202 (2024).

Calculations using the ^{16}O + ^{92}Zr collision showed that the inclusion of nuclear friction effects increased the fusion probability significantly, improving the agreement between the theoretical and experimental fusion barrier distributions Phys. Lett. B **854**, 138755 (2024).

First measurement of neutron capture on radioactive ^{204}Tl leads to reduced uncertainty in the predicted ^{204}Pb abundance, which is in agreement with solar system observations Phys. Rev. Lett. **133**, 052702 (2024).

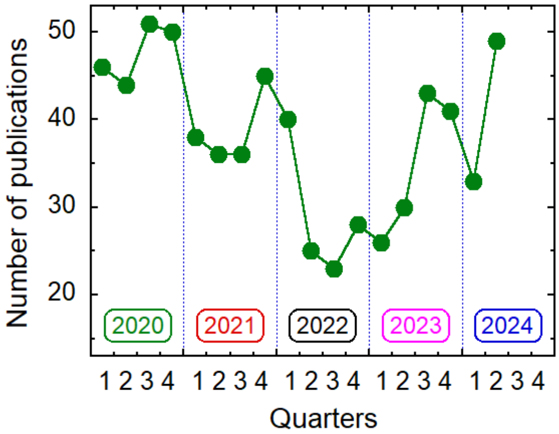

Figure 4: The aggregated Nuclear Physics publication output represented by the number of papers published in refereed journals in 2020-2024. The long-term effects of the COVID pandemic are still clearly visible. The pre-pandemic levels of about 180 publications per year were recovered only in 2024, with a deep dip in 2022 corresponding to about a two-year lag between performed experiments and publications. This also illustrates the fact that the Nuclear Physics community was particularly badly hit by travel restrictions and overseas lab closures.

Remarkably, the 2022 dip in the total number of publications coincided with a 2022 spike in those listed above as highlights.

1.3 Key questions to address

Shape evolution and coexistence in nuclei

The nuclear shape is a defining feature of how we understand and model the structure of nuclei. How the nuclear shape changes as a function of proton and neutron number, but also with excitation energy, reveals key information on how nucleons interact, especially in places where this change is abrupt. Across the nuclear chart, different phenomena have been observed that manifest as dramatic changes in shape, from the island of inversion near to ^{32}Mg, through to the onset of deformation at N=60, and up to the odd-even shape-staggering along the mercury isotopic chain. As we study isotopes further from the line of stability, the text-book models of interpreting deformed structures in nuclei begin to break down more frequently.

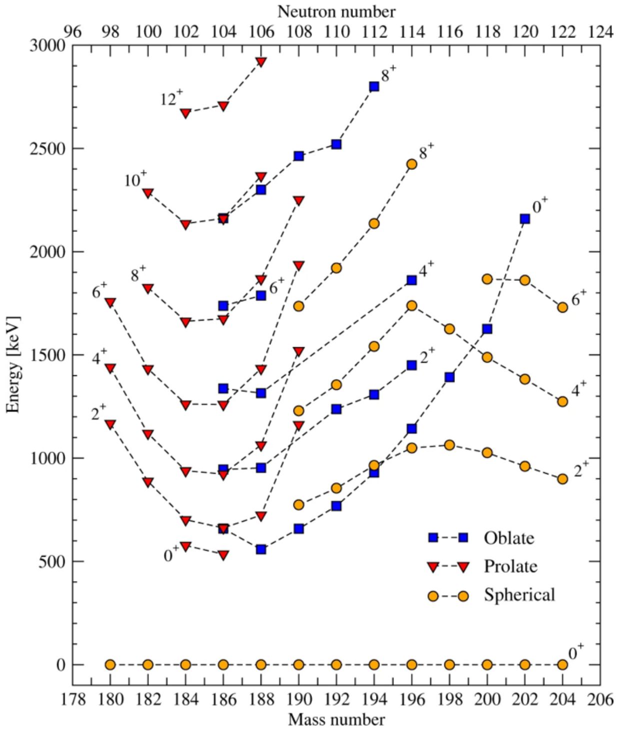

Figure 5: Different predominant shape-coexisting configurations labelled and connected with dashed lines. New data on ^{186}Pb are from an experiment performed at the University of Jyväskylä using the SAGE+RITU+GREAT instrumentation. Reproduced with permission from J. Ojala *et al.*, Communications Physics **5**, 213 (2022)

Shape coexistence in nuclei is now thought to be a universal feature across the Segré chart. In recent years, a reassessment of our understanding of low-energy excited states in nuclei has opened the door to the possibility that shape changes within a nuclear system are much more common than previously thought. There remains a large scope for the study of nuclear shape evolution and shape coexistence in exotic nuclei using techniques such as laser spectroscopy, mass spectrometry, Coulomb-excitation, few-nucleon transfer reactions, combined γ-ray and conversion electron spectroscopy, and decay spectroscopy. European facilities such as ISOLDE, GSI and JYFL are equipped with UK-led experimental setups optimised to perform shape studies using the listed techniques, and future investment at FRIB@MSU in the USA, ARIEL@TRIUMF in Canada and RIBF@RIKEN in Japan expand UK leadership in these laboratories, where access to even more exotic isotopes will be possible in the next decade.

Octupole collectivity in nuclei

Atomic nuclei have been shown to adopt asymmetric shapes for certain combinations of protons and neutrons, where the Fermi level lies between close-lying orbitals with Δj=Δl=3. This emerges from the octupole component of the nuclear strong force in the interaction between these nucleons, enhancing the collective octupole strength, leading to a pear-shaped nucleus.

Multistep Coulomb-excitation experiments have helped to distinguish stable octupole deformation from octupole vibration, as recently performed for Ra and Rn isotopes. Extensions to other actinide nuclei and also the neutron-rich lanthanide region are on-going to help understand the emergence and evolution of octupole collectivity in nuclei. Understanding the magnitude and the type of deformation is also relevant when searching for atomic electric dipole moments (EDM), where atoms and molecules containing octupole-deformed nuclei are being pursued as laboratories for such measurements. A significant non-zero value of the atomic EDM could indicate substantial CP violation, beyond the limits of the standard model. Extensions to the standard model describing large EDMs can help describe the matter-antimatter asymmetry in the Universe and thus these measurements have a high-impact discovery potential. Direct measurements of odd-mass nuclei relevant for atomic EDM measurements will be pursued, including in actinide elements, which are candidates to have the largest asymmetric deformations of all nuclei.

Exploring the boundaries of the nuclear landscape

Stable atomic nuclei are characterised by an equilibrium of their number of protons and neutrons. If this equilibrium is perturbed, the nuclei become unstable and can decay either by β decay (often followed by the emission of one or more nucleons), fission, or by directly emitting protons, neutrons, α particles or heavier clusters of nucleons. The radioactive decay properties of proton-rich nuclei give unique access to nuclear structure information far from the valley of β stability and have ramifications for the astrophysical rp-process. The development of ever more sensitive detection systems continues to make possible discoveries of new proton-rich species. Accompanied by the development of increasingly sophisticated theoretical models, this allows information about nuclear wave functions, deformations and other properties far from stability to be deduced, even in cases where only a few nuclei are produced.

The limit of nuclear binding for neutron-rich nuclei lies much further from the region of stable nuclei and can only be accessed experimentally for the lightest elements. Past studies of the most neutron-rich light nuclei have revolutionised our understanding of the forces that bind nuclei together through the discoveries of new phenomena like neutron skins and haloes. For heavy neutron-rich nuclei, measuring decay properties and neutron capture cross sections is essential if we are to understand the nucleosynthesis of elements above iron occurring in explosive environments such as neutron star mergers. Considerable progress towards this goal has been made recently in measurements of half-lives and β-delayed neutron emission probabilities, for example for nuclei near the N=50 and N=82 shell closures that lie on the r-process path. Extending these measurements to heavier systems towards the N=126 shell closure remains a challenge for the future.

Nuclear moments for fundamental interactions

Atomic nuclei and their structural properties are situated at a pivotal point in the search for new physics because they act as transmitters of the fundamental symmetry-breaking effects to the precision measurements possible in atoms and molecules. In addition, relative to competing measurements in the high-energy domain, these investigations can be performed at significantly lower costs, yet higher sensitivities. Some of the proposed signatures for sources of P and CP/T violating processes are electric dipole moments (EDM), magnetic quadrupole moments, anapole moments, and weak quadrupole moments. These properties would be the result of asymmetries in the charge or current distributions within a nuclear, atomic or molecular system.

The use of radioactive species in studies of fundamental interactions presents a promising new avenue of exploration. In particular, the use of octupole-deformed isotopes such as those found northwest of stable ^{208}Pb could be a versatile and potentially powerful tool in the study of fundamental processes. These nuclei are expected to have enhanced Schiff moments, which would amplify EDMs at the atomic level. Similarly, P- and T-violating interactions in molecules are expected to be enhanced relative to atomic systems, and scale with the atomic number, nuclear spin and nuclear deformation. Radioactive molecules, such as radium fluoride (RaF) whose laser cooling scheme was recently developed, are expected to be extremely sensitive tools in the search for new physics.

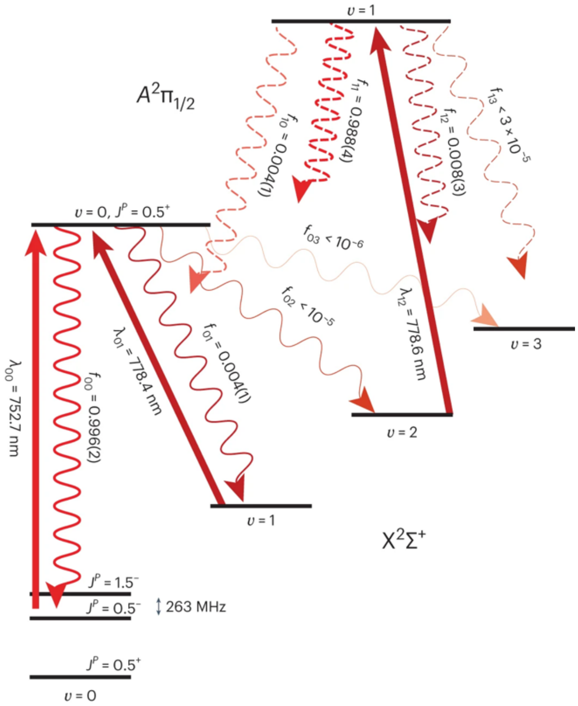

Figure 6: Proposed laser-cooling scheme for RaF. The upwards-pointing arrows represent laser excitations between the ground, $X^2\Sigma^+$, and excited, $A^2\Pi_{1/2}$, electronic states. The wavelength of each laser is shown (energy levels not shown to scale). The wavy, downwards-pointing arrows represent spontaneous emission from the (continuous lines) and (dashed lines) vibrational levels, including the associated Franck–Condon factors. Reproduced with permission from S. M. Udrescu *et al*., Nature Physics **20**, 202 (2024).

In parallel, significant progress has to be made in our ability to model these nuclear systems along with their exotic moments. Calculations are vital in guiding investigators to perform measurements on select atomic systems or producing designer molecules best suited for the search for new physics. At the same time, targeted measurements can be made based on the model predictions most sensitive to symmetry-breaking effects. These measurements will provide stringent tests of the calculations, aiding in refining their development and extrapolability to more exotic systems.

Benchmarking of theoretical modelling requires systematic investigation of higher multipole orders of the nuclear many-body system, i.e., degrees of freedom beyond the quadrupole deformation, like octupole and hexadecapole. Here, the systematic investigation of related observables is needed, such as level energies, band-structures, transition rates measured directly or extracted from lifetimes of states associated with these structures in both even-even and odd-mass nuclei. Of particular interest is the investigation of the structure of nuclei, which are good candidates to enhance CP-violating moments and possibly exploit nuclear physics techniques such as Mössbauer spectroscopy, to search for these CP-violating moments in the ground state of the nuclear quantum system.

Fission studies beyond adiabaticity and/or thermalisation

A predictive, accurate and precise description of nuclear fission, rooted in a fundamental quantum many-body theory, is one of the biggest challenges in science. Current approaches are based on adiabatic models, with internal degrees of freedom assumed to be at thermal equilibrium. However, if the fission occurs at sufficiently high energies and/or short times, the process can be non-adiabatic and/or non-thermal. To go beyond these approximations, and to obtain a unified description of fission at varying excitation energies, is of fundamental importance. The task will require building the intermediate doorway states explicitly. Those can be very efficiently modelled by known excitation operators acting on the pre-fission system. Then, one has to follow the time-evolution of such intermediate states towards fission, addressing the important challenge of describing the quantum fluctuations that build up dynamically along the pathway to fission, including those during the tunnelling process. Both steps will require state-of-the-art high-performance computing in using the most advanced computer systems along with developing efficient algorithms and programming infrastructure.

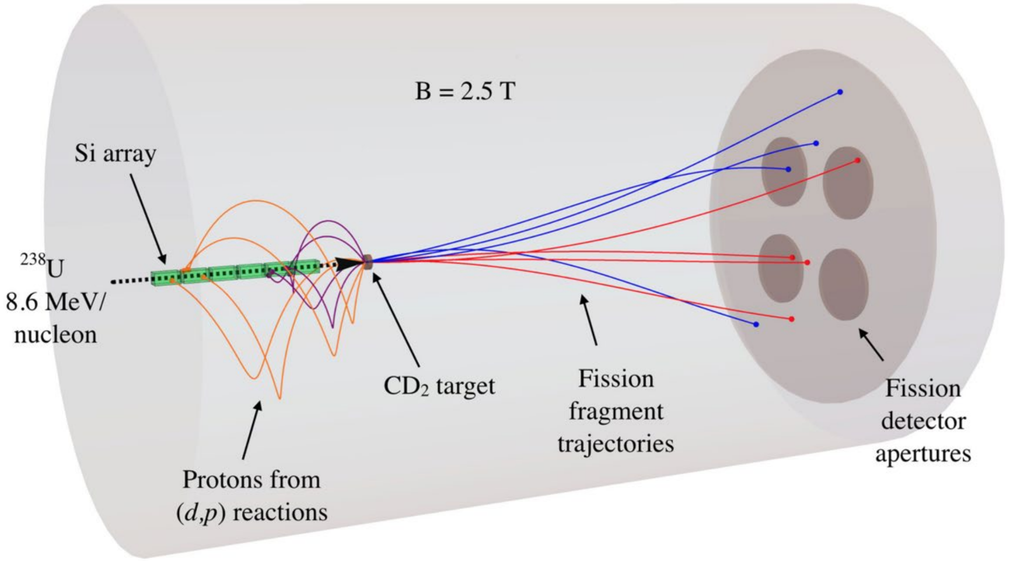

Figure 7: To-scale schematic of the experimental setup with example particle trajectories for the higher-energy deuteron-induced fission studies. Example proton trajectories for reactions populating the ground state in ^{239}U (orange curves) and states at 7 MeV close to the fission barrier (purple curves) are shown for a range of c.m. proton angles. Example fission fragment trajectories are also shown for fragments with A=138 (red curves) and A=100 (blue curves), for a range of emission angles. The experiment was carried out using HELIOS at ANL. Reproduced with permission from S. A. Bennett *et al*., Phys. Rev. Lett. **130**, 202501

Superheavy nuclei

Understanding the limits of existence for heavy and superheavy nuclei gives important insights into the factors influencing nuclear stability in the extremes. Renewed efforts worldwide to push the known elements into the 8th row of the periodic table are supported by detailed studies of the nuclear structure of lighter superheavy elements (SHE) with insights into the evolution of nuclear shells for protons and neutrons in a mass region where the differences between nucleon flavours become significant. It is quite possible that the longest-lived state in which SHE might be detectable in nature are actually isomeric states, and the study of isomers and their structure in the transfermium region provides the necessary groundwork for extrapolating to heavier systems. The atomic physics of the heaviest elements is currently accessible with modern laser-based methods up to lawrencium (Lr, Z=103) and is an area of active development. Chemical classification of the heaviest elements is approaching oganesson (Og, Z=118), potentially the heaviest noble gas in existence. UK groups have pioneered the experimental study of nuclear structure and isomers in this region and are well embedded in international collaborative efforts on all aspects of SHE research. UK theory contributions in this area include pioneering developments of fully quantum time-dependent methods to describe capture and subsequent evolution of the dinuclear system allows a microscopic understanding of the reaction mechanism for heavy ion reactions for SHE formation, as well as lighter cases of interest such as ^{12}C + ^{12}C at stellar energies.

Single-particle evolution, reaction spectroscopy

In nuclei, certain configurations of protons and neutrons are particularly well bound. These closed-shell or “magic” nuclei form the basis of the nuclear shell model; more than 60 years ago Mayer and Jensen established the magic numbers found in stable nuclei in an ad hoc manner, using a mean field plus a strong spin-orbit interaction. Exploring the formation of shell structure and how these magic configurations evolve with nucleon number towards the drip-lines is a frontier in the physics of nuclei, and a microscopic understanding from nuclear forces presents a major challenge for theory. For example, near the neutron drip line, weak binding is likely to soften the nuclear potential, leading to a much more diffused structure.

Recently, a quite surprising evolution in single-particle structure has been revealed, even in near stable and moderately neutron- or proton-rich systems. In lighter nuclei with low-level density, these changes are sufficient to destroy magic numbers observed near stability. In some cases, drifts in single-particle states have opened up new gaps in the single-particle spectra and created regions of associated stability. Similar trends in single-particle states have been observed in near-stable heavy nuclei, which point to a fairly ubiquitous and robust mechanism. Such changes have begun to be interpreted as arising from the effects of the valence nucleon interactions, where the gradual filling of, e.g., a valence neutron in a particular orbit has an increasing interaction on valence protons, driving trends in single-particle states with nucleon number. Phenomenological approaches to the theoretical understanding of shell evolution have illustrated the important contribution of tensor interactions and their interplay with central forces.

In microscopic approaches, the importance of three-body forces to shell evolution is starting to emerge. For example, N=28 is the first magic number that cannot be reproduced by the calculations using two-body nucleon-nucleon interactions alone. Several studies using chiral effective field theory for Ca isotopes have shown that the inclusion of three-body effects is essential to reproduce not only N=28, but that they also weaken a predicted shell gap at N=34. These predictions have recently been vindicated by the first measurements of excited states in C. These pioneering results suggest the major relevant effect is an additional repulsive monopole interaction between valence nucleons as a consequence of three-body effects.

These are effectively hidden in approaches such as the shell model, where empirical adjustments to N-N forces hide the neglected 3N effects. Indeed, predictions for exotic systems from these calculations are at variance to those from naive shell model, perhaps pointing to a deficiency in these adjustments or the influence of novel degrees of freedom such as the scattering continuum. Increased knowledge of the structures of exotic systems, particularly their single-particle nature, are needed to confirm the aspects of both phenomenological and microscopic approaches to the description of shell evolution and the elements of the nucleon-nucleon force in nuclear matter that drives them. This is also an issue of critical importance for understanding the astrophysical r-process.

As more exotic systems are probed, the role of the finite geometry of the nuclear potential becomes an important consideration for particles that experience no or a small centrifugal barrier. The wave functions for s- or p-states become more extended, causing the states to linger near threshold. This effect leads to halo formation for s-states and an apparent reduction in the separation between spin-orbit partners for p-states. The apparent reduction in the spin orbit separation in ^{34}Si compared to ^{36}S, with the removal of two s-state protons, has also led to the interpretation of a bubble nucleus where there is a central density depletion, which would lead to a spin orbit interaction of opposite sign to that at the nuclear surface. Robust analysis of the fragmentation of single-particle strength is needed to properly interpret these phenomena.

The best probes of the single-particle nature of nuclei are via direct reactions that excite a single-particle degree of freedom, such as transfer reactions, which are used at a range of facilities with fast or reaccelerated radioactive ion beams.

Reactor neutrinos and decay heat

Nuclear databases are of great importance in terms of nuclear applications such as reactor decay heat, the reactor antineutrino spectrum and nuclear medicine as well as nuclear astrophysics and studies of nuclear structure. It is imperative that, if they are to be used, the data must be accurate and have minimal errors. This is true for data concerning β decay and nuclear reactions. We have focussed on improving our knowledge of β decays that are important in these areas of application. It is well known that germanium detectors are a vital element in establishing β decay schemes using γ-γ coincidences. However, their efficiency is limited and falls rapidly with increasing energy. Accordingly, when one wishes to measure the β strength one may not detect many γ rays especially from states at higher energy. The answer to this pandemonium effect problem is to use Total Absorption Gamma Spectrometers (TAGS). These are composed of scintillators with an efficiency as close to 100% as one can manage. In collaboration with IFIC, Valencia, and Subatech, Nantes, the UK community has built three TAGS and used them at ISOLDE, JYFL, RIKEN and GSI to tackle many problems. It is envisioned that two of them will be modified and upgraded using scintillators with faster timing, such as $LaBr_3$. This will help in studying decays further from stability. The upgraded spectrometers will be used at accelerator facilities worldwide, but over the next decade primary focus will be on deployment at GANIL as it is upgraded. Test beam time has been secured at LISE in 2025 and will be deployed at S^3 and DESIR when they become available.

While TAS is a promising way to quantify the population of high-lying levels leading to the reactor antineutrino anomaly, less is done to investigate the structure of these levels. Indeed, at present the UK is world leading in this task using detailed high-resolution γ-ray spectroscopy. Clearly, for a full understanding of the phenomena the structure of these levels, that are populated despite a far lesser effective Q-value, is needed for further evaluation of the effect and, consequently, an enhanced understanding of the decay heat in a nuclear reactor for which the chain-reaction has ceased.

Nuclear dipole responses (electric and magnetic)

Nuclear dipole response to electromagnetic interactions encompasses a rich range of observed structure: The magnetic scissors mode; the Gamow-Teller resonances; the E1 response below the Giant Dipole Resonance (the “Pygmy Dipole Resonance”); quadrupole-octupole coupled structures. Open questions concerning these phenomena include: what is the underlying nuclear structure causing the observed enhancement of low-energy E1 strength? and what are the implications for astrophysical scenarios as well as the contribution to the enhancement in the violation of fundamental symmetries? Furthermore, is the Gamow-Teller M1 strength important for neutrino-nucleus interactions in astrophysical scenarios and in neutrino detectors?

Statistical properties of nuclei

In the regime of high level density where statistical models are indicated for the description of nuclei, work is ongoing in the investigation of level density models and the validity of the Brink-Hypothesis via the investigation of related Porter-Thomas distributions. Of particular interest is to determine the mass and shell-structure dependent energy regime when structure dominated properties blur, and a purely statistical approach is valid. This research determines the validity of such approaches to the modelling of processes encountered in nuclear astrophysics and is a necessary input to nuclear data evaluation.

Origin of heavy elements

Understanding the origin of heavy elements in explosive environments urgently needs experimental determination of the properties of participating nuclei, such as masses, lifetimes and decay branching ratios. Measuring these ground-state properties is the major motivation for many new facilitates such as FRIB and FAIR, both with strong UK leadership.

Nearly all elements heavier than iron are produced by neutron capture reactions. While the basic concepts of their production are understood, the astrophysical origin of the heavy elements remains one of the most important outstanding problems in modern physics.

About half of the heavy elements are produced in the s-process by a sequence of neutron captures and β decays close to the stability valley. Current models suggest this process happens during quiescent burning phases in intermediate mass stars (1-5 solar masses) and in massive stars, which later explode as core collapse supernovae. Neutron source and neutron capture reaction cross sections are a key input to stellar models predicting s-process nucleosynthesis.

The low-energy cross section of the ^{13}C(α,n)^{16}O neutron source reaction has recently been successfully measured at the LUNA 400kV accelerator, but discrepancies between previous data sets remain at high energies, which require further investigations. For the ^{22}Ne(α,n)^{25}Mg neutron source reaction, no direct measurements exist at low energies and only upper limits are available which date back to over 20 years ago.

Stellar models require neutron capture cross sections with uncertainties below 5% for stable isotopes, hence more high precision measurements are still needed in particular for low and intermediate mass nuclei. A key ingredient to deduce the stellar conditions in s-process environments, such as neutron densities and temperatures, is the measurement of branching point nuclei. These are isotopes with long half-lives, for which neutron capture competes with β decay and the reaction path branches. Direct measurements of these reactions are challenging since a radioactive target of sufficient mass is required. Some of these branching points have been successfully measured, for example at the CERN n_TOF facility, and further measurements are being planned. In addition to n_TOF, UK scientists have also ongoing involvement at the neutron facilities of the Joint Research Center Geel and ILL Grenoble. The high neutron flux facility at Birmingham will also open up new avenues to study stellar neutron cross sections.

The other half of the heavy elements is thought to be produced by the r-process. This process happens in explosive environments of high neutron densities, and involves nuclear reactions on short-lived, exotic nuclei far from stability. The astrophysical sites where this process can take place are a long-standing open question. The recent multi-messenger observations of the gravitational waves from the GW170817 merger and the electromagnetic counterpart, provided direct evidence that heavy elements, including up to the lanthanide region, were produced by an r-process event. However, details of the production route remain a mystery as key nuclear properties, particularly precision masses and decay properties, are missing. UK scientists have strong leadership in the measurement of exotic masses and decays at e.g. TRIUMF, GSI-FAIR, JYFL, ISOLDE, and RIKEN RIBF.

The abundances of a comparatively small number of rare proton-rich heavy isotopes cannot be explained by the s- or r-processes: these are the p-nuclei. They are thought to be produced by photodisintegration reactions of pre-existing seed nuclei in the outer shells of exploding massive stars. Although this process occurs naturally in supernovae and is able to produce the bulk of p-nuclides within a single site, a longstanding problem relates to abundances of p-nuclei with $A < 110$ such as ^{92,94}Mo and ^{96}Ru which are two orders of magnitude more abundant in the solar system than expected. UK scientists are at the forefront of novel proton capture measurements, relevant for the production of astrophysical p-nuclei using the ESR heavy ion storage ring at GSI, developing a silicon strip detection system to be used at the ESR. The

CARME system installed at the GSI CRYRING, developed within the UK ISOL-SRS project, will allow the study of further key nuclear reactions for the p-process.

Creation of CNO nuclei in first generation stars

First-generation stars formed out of primordial hydrogen and helium soon after the Big Bang. Being very massive (up to 1000 solar masses), they could not have supported themselves against gravitational collapse by fusing hydrogen through the pp chain, simply because this process is too inefficient. Instead, they would have needed carbon, nitrogen, and oxygen to catalyse hydrogen burning through the much more efficient CNO cycle. However, the origin of CNO elements in such stars remains highly uncertain. New fusion processes have recently been proposed to bridge the A=5 and 8 nuclear mass gaps and efficiently convert primordial light elements into CNO nuclei. These processes, however, rely on nuclear clustering effects at low energies (much akin to enhanced fusion of three α particles through the Hoyle state in ^{12}C) which still await experimental confirmation. A series of experiments, already proposed at LUNA, will investigate reactions with charged particles in the exit channel using a purpose build silicon-detection array developed in Edinburgh.

Anomalous electron screening observed in the laboratory

The presence of electrons around interacting nuclei in fusion reactions, both in stellar plasmas and in laboratory experiments, reduces the Coulomb repulsion between the positive charges and leads to enhanced cross sections at the lowest energies. To correctly interpret experimental data and describe fusion reactions in stars, the electron screening effect must be well understood. Yet, experimental values of screening potentials often exceed theoretical limits and the origin of such a discrepancy remains unknown. Intriguingly, the discrepancy is larger for reactions involving nuclei with a strong cluster structure, which has led some authors to propose that nuclear clustering may be responsible for the anomalous enhancement in the fusion cross sections. The significantly reduced background at LUNA will afford unique conditions to explore this phenomenon at the lowest accessible energies and provide further insights on the long-standing problem of electron screening.

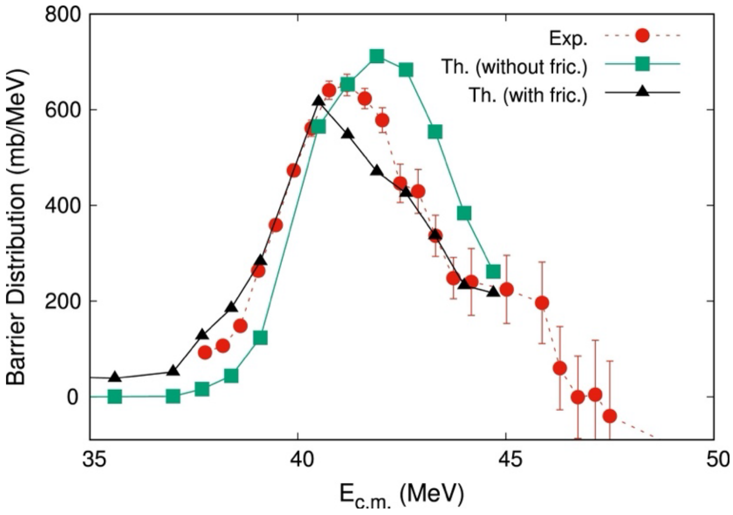

Figure 8: The theoretical and experimental fusion barrier distributions for $^{16}O + ^{92}Zr$. The calculated theoretical values with friction (black triangles) are an improvement on the same calculations without friction (green squares). Reproduced with permission from I. Lee *et al*. Phys. Lett. B 854, 138755 (2024).

Nuclear solution to the cosmological lithium problem

The abundance of primordial lithium, created in the first few minutes of cosmic time, is inferred from the spectroscopic analyses of extremely metal poor (EMP) stars, believed to be the direct descendants of first-generation stars. Since the depletion rate of ^{7}Li in EMP stars is believed to be negligible, such observations should reflect the amount of lithium created during BBN. However, the observed lithium abundance is only one third of the amount predicted, leading to the so-called cosmological lithium problem. Could lithium have been destroyed in the first stars? To answer this question, and possibly solve the cosmological lithium problems, α-capture reactions on lithium isotopes must be studied at the lowest accessible energies. These will be the focus of future studies at LUNA by prompt γ-ray detection and using α beams over a wide energy range.

Evolution and death of massive stars

Stars with masses above 8-10 solar masses are expected to die as supernovae at the end of their evolution. However, the exact mass that dictates whether they leave behind a neutron star or a black hole is highly uncertain and sensitively depends on the rate of the carbon fusion reactions ^{12}C+^{12}C. To date, no measurement has been carried out directly at the energies of interest because of the extremely small cross sections involved. New underground measurements are expected to provide key insights on these important reactions.

Core metallicity of the Sun

Helioseismology observations have recently provided information on the internal chemical composition of the Sun which, however, remains at odds with predictions from the Solar Standard Model. To address this discrepancy, dubbed as the solar metallicity problem, renewed efforts to study the ^{14}N(p,γ)^{15}O reaction are needed.

Structure of hadrons and the dynamics of QCD

Understanding the internal structure of hadrons and the dynamics of QCD is one of the main drivers of current and next generation international hadron structure research programmes, both experimentally and theoretically.

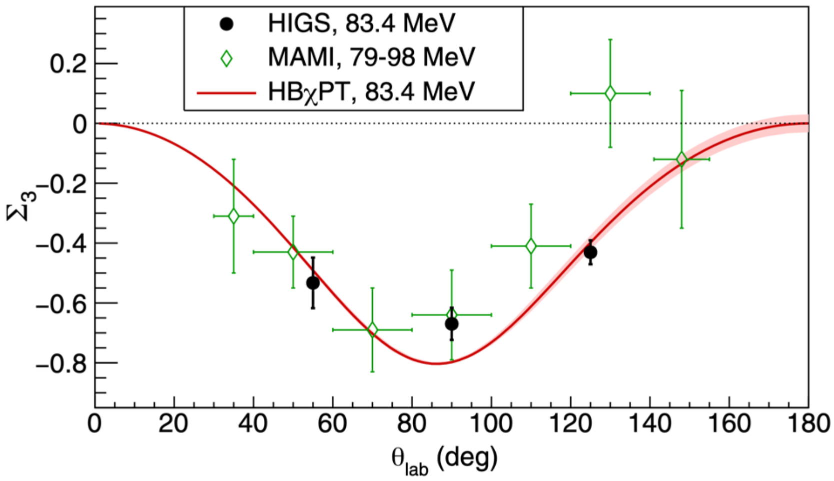

Figure 9: The photon beam asymmetry Σ3 obtained in the experiment performed at the High Intensity Gamma-Ray Source facility at the Triangle Universities Nuclear Laboratory (circles) compared to the results from MAMI (diamonds). The error bars include statistical and point-to-point systematic uncertainties only. The curve with the 1σ error band is the theoretical Σ3 implied by the measured polarizabilities using the χEFT framework. Reproduced with permission from X. Li *et al.*, Phys. Rev. Lett. **128,** 132502 (2022).

QCD is characterised by still poorly understood emergent phenomena at low energies in the non-perturbative regime on the mass scale of hadrons, namely confinement and the dynamic generation of mass and spin. Precision mapping of the internal structure of hadrons, extracting the spatial distribution and the motion of quarks and gluons within them, sheds light on these topics and improves our knowledge of the dynamics responsible for the characteristic properties of hadrons. High-precision studies of the hadron mass energy scale have only recently truly begun, and there remains a large array of experiments demanding further investigation.

Lepton-nucleon scattering is a very clean probe for hadron structure, and JLab is the foremost facility for studying the emergent phenomena of QCD. New possibilities have arisen within the last decade due to JLab upgrading its electron beam energy to 12GeV, which offers a broad phase space. JLab also hosts the capability to operate at the world’s high-luminosity frontier, allowing for high-precision measurements and observations of extremely rare processes. As such, high current, spin polarised electrons, as well as high resolution spectrometers and spin polarised targets, facilitate a vibrant hadron structure programme in the CLAS12, Hall A and Hall C JLab collaborations.

The hadron structure programme encompasses many measurements. On-going elastic electron-nucleon experiments in Hall A at JLab, with the BigBite (BB) spectrometer and Super Bigbite Spectrometer (SBS), are measuring the Sachs electromagnetic form factors of the nucleon at the highest ever momenta transfer squared, as well as two-photon exchanges in the electron-nucleon interaction. The UK plays a leading role in the SBS programme, contributing to hardware and the physics programme. Several hadron structure experiments with SBS are also planned in the next decade. JLab results have recently started emerging from hard exclusive scattering experiments such as Deeply Virtual Compton Scattering (DVCS), and Timelike Compton Scattering (TCS). Such reactions provide access to hadron tomography on the femtometer scale via extraction of GPDs. Other future experiments exploiting deep scattering processes related to hadron tomography include deeply virtual meson production, and Semi-Inclusive Deep Inelastic Scattering (SIDIS).

Light meson structure studies, namely of the pion and kaon, are also key for studying the dynamics of QCD, in particular emergent hadronic mass. These mesons can be accessed via the Sullivan process – hard scattering from the virtual meson cloud of the nucleon. Pion and kaon elastic form factor studies have recently been performed at JLab. In addition to hadronic mass, the evolution of these form factors is one of the cleanest ways to study the transition between the two distinct regimes of QCD. Furthermore, a future programme of Tagged DIS (TDIS) measurements are planned to extract the inclusive structure functions for the pion and the kaon. TDIS will also offer insights into the elusive mesonic content of the nucleon, which remains largely unknown and yet plays an important role in nuclear physics (for example in the N-N interaction).

J/psi physics is a further topic of study at Jlab, which is currently at the leading edge of hadronic physics. It provides access to gluonic form factors of the nucleon, distribution of colour charge and the emergence of hadronic mass. Interactions of the bare quarks with the gluon field, via the process of dynamical chiral symmetry breaking, can be related to the trace anomaly of the QCD energy-momentum tensor. Dominant at the scale of the nucleon mass, insight into this trace anomaly can be gathered by measuring quarkonium production near threshold (at energies of ~8–10 GeV), in which the J/psi, dominated by the real part of the scattering amplitude, couples only to the gluons and not to light quarks. Furthermore, probing the production mechanism, for example via (quasi-real) photoproduction, is a vital tool in these studies.

Complimentary tools for hadron structure are available via pion, kaon and proton beams (and their anti-particles) at the CERN SPS M2 beamline, via the AMBER/NA66 collaboration. Meson structure can be accessed through Drell-Yan measurements and prompt photon production. Emergent properties can be studied through mesons and baryon radius measurements in inverse kinematics and the study of meson polarisabilities through Primakoff reactions.

Looking beyond the next decade, UK physicists are leading developments of the hadron structure programme at the EIC. This includes, for example, DVCS, TCS, TDIS and meson form factors. Whilst JLab allows for precision QCD studies in the valence regime, the EIC will unlock a new kinematic regime reaching into the low-x region, with unprecedented precision.

The spectrum of hadronic states

Hadron resonances are studied by UK nuclear physicists using fixed targets at JLab (CLAS12 and GlueX collaborations) and at the Mainz Microtron (MAMI) in Germany. The UK hadron physics community is also studying the excitation spectrum of light and heavy quark mesons, primarily at JLab employing the UK funded equipment contribution to CLAS12 (the forward tagger apparatus).

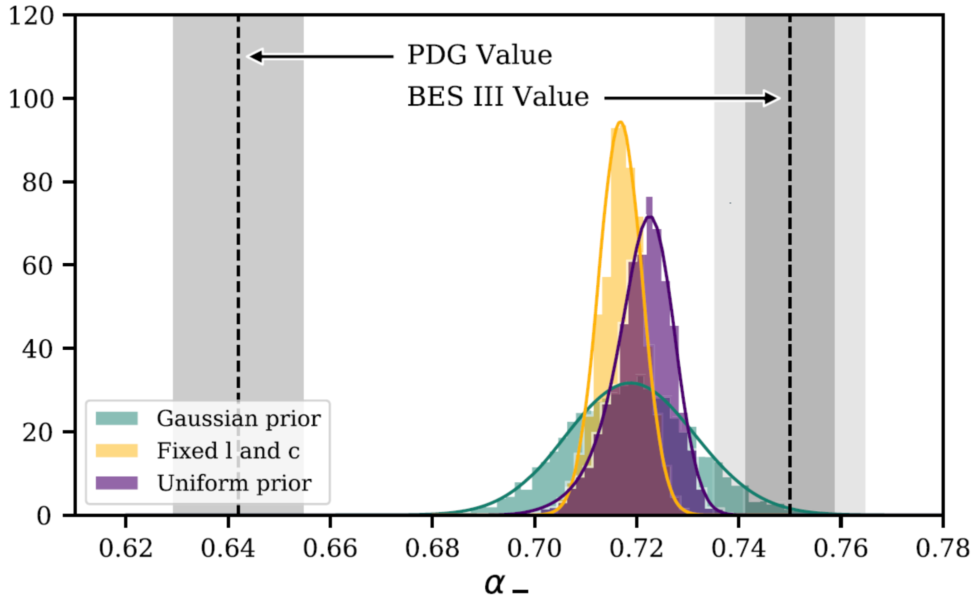

Figure 10: Posterior densities for the weak decay parameter $\alpha-$ of the Λ, given different priors for the beam polarization calibration constants $P\gamma C$ and $P\gamma L$. The histograms show the result of the MCMC sampling of the marginalized posterior densities while the solid lines represent a direct scan of the posteriors. Dark grey vertical bands represent statistical uncertainty; the additional light grey bands on the BESIII result represent systematic uncertainty. Reproduced with permission from D. G. Ireland *et al*., Phys. Rev. Lett. **123**, 182301 (2019).

In the coming decade, next-generation measurements will allow the full spectroscopy of hadronic particles containing strange quarks to be detailed for the first time. In addition, the production of unprecedented quantities of such particles in clean environments will enable their interaction with nucleons and nuclei to be elucidated. This will be a crucial advancement in the field - strange quark containing hadrons are predicted to play a key role in neutron star physics, in hadronisation following the big bang, and provide unique constraints on QCD. Intense electromagnetic beams will provide reach into this strange quark sector. However, comprehensive determination, including reaching high-statistical samples of particles with the maximum strangeness content, will employ beams of unstable strange quark containing particles (neutral Kaon mesons) created from next generation compact photon source technologies at JLab. This first clean and intense strange particle beam facility, the K-Long Facility at JLab, will be realised with a UK lead.

The UK also leads efforts to establish a spectroscopy programme at the EIC. This will facilitate a complementary programme with colleagues in Particle Physics allowing us to learn about the structure as well as the spectroscopy of states previously only seen in high energy experiments. Further complementary studies of the strange meson spectrum are available via the AMBER/NA66 collaboration, with detailed study of the excitation spectrum of strange mesons and their decay products being available, to add to the hunt for exotic meson states.

Heavy-Ion Collisions to study strongly interacting matter

Ultra-relativistic heavy-ion collisions at hadron colliders provide the only way to explore the phase transitions of QCD, a non-Abelian fundamental quantum field theory, in the laboratory. Measurements at ALICE and the planned ALICE 3 detector use high-energy hadronic collisions and the production of the quark gluon plasma as a laboratory to study the strong interaction in extreme regimes. This allows addressing properties of QCD that cannot be studied in other contexts. Examples include:

- What is the nature of interactions between high-energy quarks and gluons and the quark–gluon plasma?
- How do transport properties arise from first-principle quantum chromodynamics?
- To what extent do quarks of different mass reach thermal equilibrium within the plasma?

The interactions are frequently modelled by considering radiative and collisional processes. Several approaches to including the nonperturbative nature of the interactions. However, further experimental input is required to show what the appropriate description is. As the processes depend on the masses and momenta of the quarks, precise measurements of different flavours can disentangle the contributions. ALICE is set up particularly to allow such measurements down to low momenta, where thermalised quarks would appear. Quantum interference effects of radiative interactions can be studied by comparing measurements with different system sizes. Towards run 5 and beyond, precise measurements of charm-charm will also help to disentangle different effects.

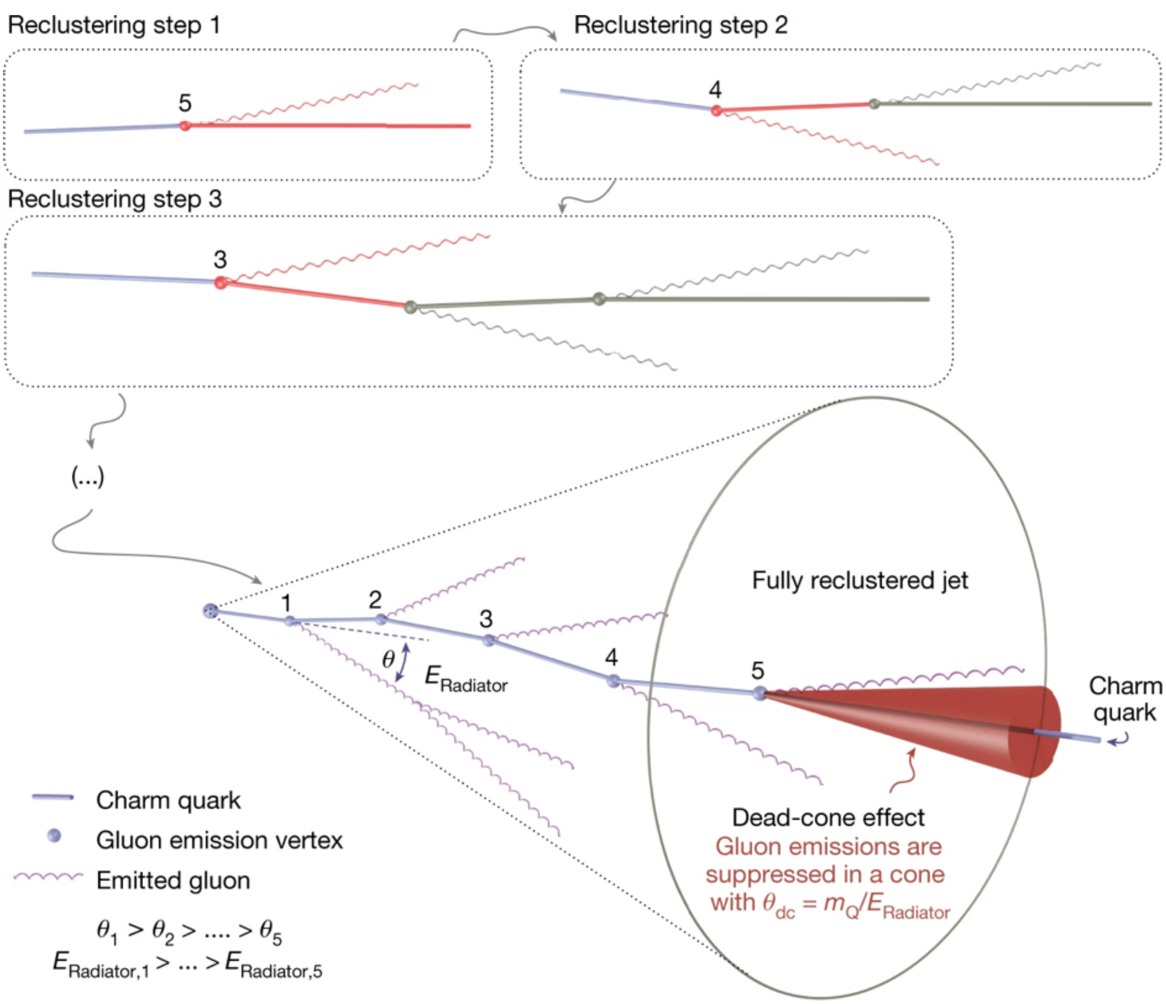

Figure 11: A sketch detailing the reconstruction of the showering charm quark, using iterative declustering, is presented. The top panels show the initial reclustering procedure with the C/A algorithm, in which the particles separated by the smallest angles are brought together first. Once the reclustering is complete, the declustering procedure is carried out by unwinding the reclustering history. Reproduced with permission from ALICE Collaboration, Nature **605**, 440 (2022).

How do partons transition to hadrons as the quark–gluon plasma cools down? How does this process differ from hadron formation in elementary collisions?

The production of hadrons in heavy ion collisions is studied by the measurement of different hadron species. In particular, heavy flavour quarks end up in one of the different heavy flavour hadrons. With the data taken in run 3 and beyond and the detector upgrades, the production of different heavy flavour hadron species can now be measured at unprecedented accuracy. By comparing the production in different collision systems and multiplicities, the puzzle of baryon production can be addressed. Measuring a large part of the hadron spectrum is also a prerequisite for understanding the interaction of quarks with the QGP as described above. With ALICE 3, measurements of multiply charmed baryons and exotica are also in reach and can provide much more thorough input into hadronisation processes.

What are the mechanisms for the restoration of chiral symmetry in the quark–gluon plasma? What are the conditions in the QGP? Which mechanisms drive strongly interacting matter towards equilibrium? How do they behave close to the diffusion regime?

The deconfinement and chiral restoration transitions of hadronic matter seem to be connected. A signal for chiral restoration can be found in the mixing of the meson with its chiral partner, the a1. It is measured via the electron-positron pair in the decay. In addition, dilepton pairs from the QGP pass the medium unhindered and can give insight into the conditions in the medium itself and its evolution. This can constrain the understanding of the initial conditions and about the hydrodynamic evolution, while measurements of thermalised hadrons inform about the state of the evolution.

How do hadronic systems evolve when going from hadron production in small systems and multiplicities to heavy ion collisions?

As many of the variables used for studying the QGP show an unexpectedly smooth transition to smaller systems, it is important to understand how these are related. The appearance of flow signatures in pPb and pp collisions puts our current understanding of the nature of these systems into question. In addition, the qualitative success of hadronisation models based on a thermally equilibrated hadron gas in systems where this would not be expected shows that there is much to learn about hadronic particle production. In hadronic interactions, several experiments also found a large increase in soft photon production, far above the soft limit of quantum electrodynamics, which may be related to hadron production. The production of hadrons in many different collision systems will be addressed with high accuracy with ALICE. For ALICE 3 a dedicated detector will measure soft photon production in hadronic collisions. In this way, the puzzles about the nature of hadronic collisions can be addressed.

2. International context

The research topics of the UK Nuclear Physics community in general are well aligned with equivalent international long-term planning roadmap documents. For example, the USA Nuclear Science Advisory Committee (NSAC) Long Range Plan for nuclear science (LRP) which was released in 2023, and we anticipate alignment with the NuPECC LRP, which will be released towards the end of the year 2024. UK-based nuclear physicists have been involved in the writing and editorial process of the NuPECC LRP. This alignment is bolstered by the fact that many of the UK Nuclear activities happen within international collaborations and at worldwide facilities, and due to leadership exhibited by UK-based nuclear physicists in international collaborations.

The top-level recommendations in the NSAC LRP include continued investment in development of new techniques and exploitation of existing facilities in the US that are synergistic with the UK community’s own goals of exploitation of the best facilities for specific measurements and developing new technologies to maintain our international leadership. The NSAC LRP also advises the expeditious completion of the EIC as the highest priority for facility construction, which aligns with planned activities of the UK-based EIC community over the next decade. Additionally, the NSAC LRP recommends the construction of a 1-tonne neutrinoless double β decay experiment - with LEGEND selected as a potential choice for this.

Lattice QCD groups in the UK play a key role in international collaborations and perform world-leading calculations of excited hadrons and hadron resonances. Work in this area connects with the US NSAC LRP 2023 which states that "a combination of novel theoretical ideas and use of world-leading computation facilities has led to transformative progress that enables new areas of study for the spectrum, structure, and interactions of hadrons [...]".

The NuPECC LRP has been approved but not published yet. The current recommendations include, but are not limited to:

- The realisation and exploitation of European facilities including the completion of FAIR, exploitation of S^3 and DESIR at GANIL/SPIRAL2, diverse research at CERN through ISOLDE, ALICE 3, n_TOF, and the North Area, developing ISOL facilities, and exploitation of lepton beam facilities.
- Continued support for JLab in the USA, as well as AMBER at CERN, and MESA in Germany.
- The construction of ALICE 3 as part of the HL-LHC plans is strongly supported. Upgrades to ATLAS, CMS, and LHCb should also be exploited for heavy-ion physics.
- Completion of AGATA-4π to push the frontiers of γ-ray spectroscopy.
- Support for current and future storage rings for precision measurements at FAIR and ISOLDE.
- Support for theory centres and increased numbers of positions for early-career researchers to develop a unified theoretical description of nuclei and nuclear matter.

Continued development of semiconductor, gaseous, scintillation technologies and readout electronics for a range of radiation detection techniques.

Roles and Needs for High Performance Computing

Computing review and strategy development activities for Nuclear Physics have been taking place both in Europe and in the USA in the last years.

In 2016, the US Department of Energy (DOE) commissioned an Exascale Requirements Review for the nuclear physics programme in the USA, where the scientific challenges and opportunities in nuclear physics that could benefit from exascale computing have been identified. This review informed the 2023 Long Range Plan for Nuclear Science produced for DOE, National Science Foundation (NSF), and Nuclear Science Advisory Committee (NSAC). This LRP has identified the emerging technologies in computing (High Performance Computing, Artificial Intelligence and Machine Learning technologies, Quantum Computing) as key cross-cutting opportunities for advancing scientific discoveries in nuclear physics, and its applications for society (Recommendation 4 of the plan).

At the European level, in 2022, in the context of the Joint ECFA-NuPECC-APPEC (JENAA) activities, initiatives started for development of a common strategy for the federated large-scale computing infrastructures to serve the three scientific communities. This initiative has identified computing for nuclear physics as currently being mainly facility based, with limited access to the national computing infrastructures, making the scaling-up for the forthcoming large-scale experiments difficult.

To address this challenge, the synergies and the commonalities of computing in the three fields started to be explored at a first workshop in June 2023 (Bologna, Italy). The workshop generated a working group structure organised around five major areas. The working groups have been mandated to develop reports and recommendations which will be incorporated in the joint “JENA Europeans White Paper on Federated Computing” to be presented at the JENA Symposium in Spring 2025.

The UK is active in this process, with experts from Brunel and Glasgow universities, and from the STFC laboratories involved both in the Bologna’s workshop and the follow-up working groups.

3. Facilities

3.1 Nuclear Structure Physics and Nuclear Astrophysics

Experimental studies are conducted at facilities equipped to deliver stable or exotic nuclei across a wide range of energies and intensities. The suitability of a facility for a particular study depends on several factors: the available beams, the specific observables of interest, and the experimental techniques required to investigate them. As a result, the scientific community utilises the most advanced and appropriate facilities available. These facilities are generally classified into stable beam, fragmentation, and ISOL facilities.

Low-energy (<60 keV) radioactive ion beams produced at ISOL facilities such as **ISOLDE-CERN** and **ISAC-TRIUMF** are characterised by high purity, high quality (low energy spread and emittance) and high intensity. These properties are essential for a range of experimental techniques, such as decay spectroscopy, laser spectroscopy and re-acceleration. Fragmentation facilities, such as **FRIB**, **RIBF-RIKEN** and **GSI/FAIR**, 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, allowing the study of more exotic nuclei, and to the independence from chemical effects inherent in the fragmentation method. Stable-beam facilities like **Argonne National Laboratory (Chicago), INFN-LNL (Legnaro)** and **JYFL (Jyväskylä)** provide high-intensity stable beams that enable precision studies of nuclei at or near stability. The UK nuclear structure community leads a global science programme with significant leadership at many of these world-leading facilities.

The **SPIRAL2 facility at GANIL** will provide new opportunities in terms of exotic beams, complementary in scope to existing facilities in Europe, and further in the future a new facility at **Legnaro (SPES)** will provide increased capacity of ISOL beams to the international community. The AGATA spectrometer for example has already exploited intense stable beams at these facilities but will benefit further from the new opportunities at these facilities and FAIR.

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 attempting to study their properties or indeed their interactions with other nuclei. Neutron capture reactions play a major role in the production of the elements heavier than iron. Key neutron induced reaction cross sections are studied at cutting edge neutron facilities, such as **n_TOF CERN**, the **Joint Research Center Geel** and **ILL Grenoble**.

The UK Nuclear Astrophysics community leads experiments at international facilities including **TRIUMF**, **ANL**, **FRIB**, **n_TOF** and **ISOLDE**, 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, like the study of explosive astrophysical events such as neutron star mergers. Major developments in beams of exotic nuclei at existing laboratories continue apace, and the newest facilities such as **FRIB**, and in the future **FAIR**, will provide ever more exotic nuclear systems to study the reaction processes that occur in explosive astrophysical environments to produce the chemical elements.

The UK community needs to be able to respond quickly to new opportunities at these facilities, in particular in maintaining its international role in the provision of cutting-edge technologies. 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 R^3B experiments (part of the NUSTAR collaboration at FAIR) some of which have already been exploited at RIKEN and other laboratories. The ISOL-SRS project has resulted in two spectrometers for the study of direct reactions at ISOLDE (ISOLDE Solenoidal Spectrometer) and at CRYRING at GSI (CARME). New projects will provide UK leadership at the new FRIB facility in the US through FAUST and to the RIBF-RIKEN nuclear physics programme with HYPATIA.

ISOL facilities: Precision frontier

Within Europe**, ISOLDE** is the world leading ISOL facility, with access to over 700 radioactive beams with half-lives down to milliseconds. As well as low-energy beams, the now fully commissioned HIE-ISOLDE superconducting linear accelerator can accelerate beams up to 10MeV/u for nuclear reaction measurements. The beams from ISOLDE are used in a very rich scientific programme including precision measurements of nuclear properties such as masses, electromagnetic moments, radii, and spins; studies of radioactive decay; and reaction studies using Coulomb excitation, inelastic scattering, and transfer reactions. These experiments focus on nuclear structure and reactions, but also include measurements with nuclear astrophysical significance and those that make searches for “new physics” beyond the Standard Model of particle physics. Measurements of hyperfine effects are also used to address aspects of atomic and molecular physics. The UK has a significant presence at ISOLDE with around 12% of all registered users coming from the UK and has led research on the majority of experimental stations at the facility with significant leadership in both the COLLAPS and CRIS laser spectroscopy setups, the ISOLDE decay station, Miniball, the SPEDE electron spectrometer, and the ISOLDE Solenoidal Spectrometer (part of the STFC-funded ISOL-SRS project). A few limited examples of emerging important science areas relevant for the UK community give a flavour of the scientific opportunities in exploiting ISOLDE during the next decade.

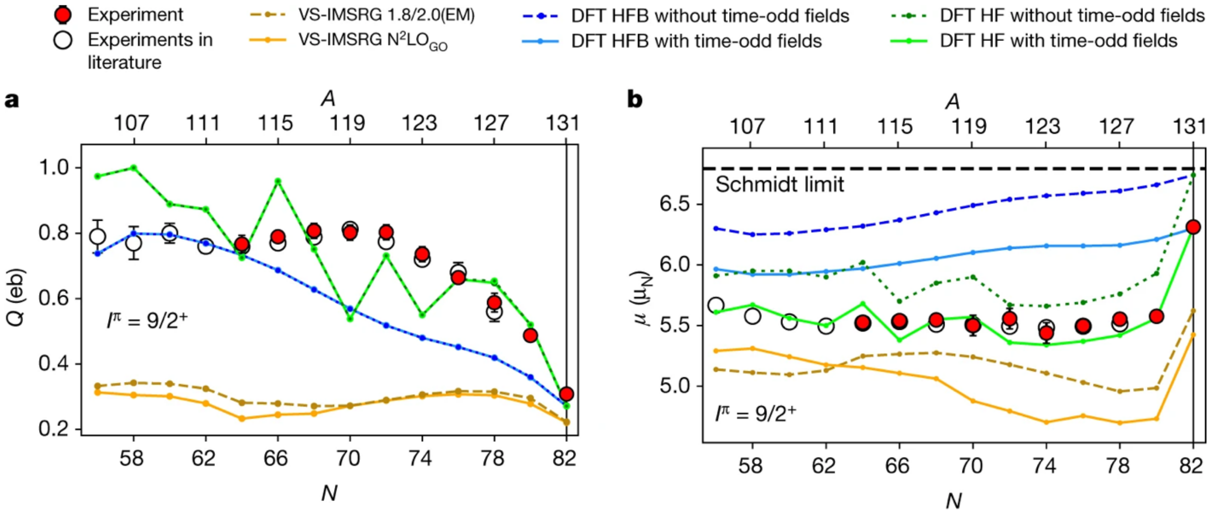

Figure 12: The indium electric quadrupole moments (**a**) and magnetic dipole moments (**b**). The horizontal dotted line indicates the single-particle value (Schmidt limit). Experimental results (red dots), obtained using the collinear resonance ionization spectroscopy (CRIS) technique at the ISOLDE facility of CERN, are compared with theoretical calculations from *ab initio* VS-IMSRG and DFT. Reproduced with permission from A. R. Vernon *et al*., Nature **607**, 260 (2022).

Radioactive decay

Studies of radioactive decay modes have been a central topic of science programmes since the very beginning of ISOLDE, which have grown in importance in areas such as nuclear structure, nuclear engineering, and astrophysics. Equipment and techniques are in continuous development and the ISOLDE Decay Station (IDS) is a permanent installation, with strong UK involvement, attempting to cover all possible decay modes, incorporating fast timing and spectroscopy in measurements of proton, α, β, γ decays and neutron emission. Studies are made of the very lightest species that fragment into charged particles, through to β-delayed fission in the heaviest systems.

Reactions with post-accelerated beams: The development of the HIE-ISOLDE accelerator has allowed an increase in the energies of post-accelerated beams in stages, up to its completion in 2018. Beams are delivered to three beam lines that host a newly refurbished array of germanium detectors (Miniball), a solenoidal spectrometer for direct reaction studies (ISS) commissioned in 2018, both with significant UK leadership, and a scattering chamber. The availability of beams with an energy of around 10 MeV/u will open new potential, for example, to explore multi-nucleon transfer, moment measurements by recoil-in-vacuum methods and to probe fission via transfer-induced reactions.

Radioactive molecules

Precision measurements of radioactive molecules open a wealth of opportunities in physics and chemistry. Recent pioneering measurements at CRIS, led by the UK, have shown it is possible to form molecules involving radioactive isotopes and to perform high-resolution molecular spectroscopy. A simple pragmatic opportunity that follows is to extend laser spectroscopic measurements of ground-state properties of nuclei to cases where the atomic or ionic properties are insensitive, or where the isotopes are only produced in molecular form. However, more importantly, molecules also provide a route for studying symmetry-violating phenomena relevant to particle physics. The appearance of such effects scales dramatically with atomic number and nuclear deformation; for example, studies of molecules containing (necessarily radioactive) heavy octupole deformed nuclei show several orders of magnitude enhanced sensitivity to electric dipole moments.

TRIUMF is home to the only ISOL facility in North America, ISAC. Radioactive ion beams are available at low energies for precision experiments but can also be accelerated to energies relevant to astrophysics environments. The UK community engages and leads a wide range of nuclear astrophysics and nuclear structure research at both ISAC I (low energy beams) and ISAC II (accelerated beams). The UK is by far the largest international user group, holding many leading positions within the user base. Experiments include reaction studies employing the DRAGON, TUDA (TRIUMF-UK-Detector-Array) and EMMA facilities as well as precision experiments via the TITAN and GRIFIN setups.

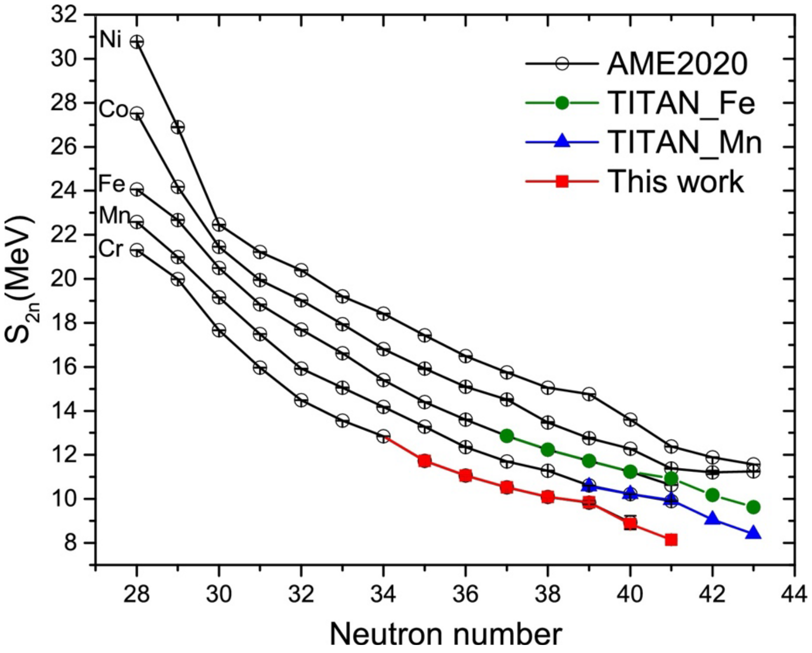

Figure 13: Two-neutron separation energy (in MeV) for Ni (Z=28) through Cr (Z=24) measured at the Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) at TRIUMF's TITAN facility is shown including the comparisons with AME2020. For Fe and Mn, recent TITAN measurements are also shown. Reproduced with permission from R. Silwal *et al*., Phys. Lett. B **833**,137288 (2022)

The **IGISOL facility at the University of Jyväskylä** utilises gas catching techniques to access elements that are not readily available at ISOLDE and TRIUMF and therefore provides a complementary tool for refractory cases. The UK nuclear physics community has a well-established track of leadership in the experimental programme at JYFL, which has been one of the most in-demand facilities over successive consolidated grant rounds. The UK has invested in major instrumentation projects at JYFL over many years and continues to exploit these investments heavily.

The UK also provides ongoing technical support, particularly in the areas of data acquisition and mechanical design. It has a plethora of spokesperson roles in decay spectroscopy using the MARA & RITU recoil separators and in-beam spectroscopy experiment using the JUROGAM and SAGE spectrometers and this is reflected in the large number of UK PhD theses based on data collected from JYFL. These experiments generally exploit fusion-evaporation reactions to explore the structure of extremely proton-rich and superheavy nuclei, and have led the international field with regard to precision measurements in these areas. JYFL also offers important opportunities for students to gain hands-on experience and training in all aspects of running experiments.

The future science programme at JYFL will continue to exploit these devices, as well as the MARA Low-Energy Branch (MARA-LEB) that is currently under development. MARA-LEB will open new opportunities for precision studies of exotic nuclei, combining the advantages of recoil separation using MARA, with gas-catcher, laser ionisation, mass spectrometry, and decay spectroscopy techniques.

Fragmentation facilities: Discovery frontier

The recently opened **Facility for Rare Isotope Beams (FRIB),** in the USA, represents a step change for nuclear physics research. With an ultimate power goal of 400 kW (an order of magnitude greater than existing facilities), FRIB is poised to become the world's premier fragmentation facility, providing an immense range of intense, radioactive beams at the frontiers of stability. FRIB has the capability to produce radioactive beams over an exceptionally wide range of energies (~1 – 200 MeV/u), by slowing down, stopping or reaccelerating the beams, allowing for the investigation of nuclear properties using a variety of methodologies.

Using the radioactive beams available at FRIB, it will be possible to search for answers to fundamental questions about the cosmic origin of the elements, the structure of atomic nuclei, and the forces that shape the evolution of the Universe. Specifically, due to the large energy range and availability of rare isotopic species, this includes direct measurements of astrophysical reactions, single-nucleon transfer reactions, which probe the quantum structure of nuclei, as well as charge-exchange reactions that reveal important facets of weak nuclear processes.

The FRIB facility has currently been in operation for ~1 year and has delivered >5000 hours of beam time for experiments. These experiments are largely led by external collaborators and FRIB boasts an impressive user community of ~1300 scientists from around the world. The UK already has a considerable science presence at FRIB, leading three of the very first experiments to be performed at the facility. However, over the next few years, the UK aims to cement its leadership at FRIB with the development of the advanced FAUST silicon detector array project. The FAUST detection system, which will work in conjunction with the GRETINA (and soon-to-be GRETA) γ-ray tracking array, will take advantage of the full range, intensity and energy of FRIB beams and push the experimental programme to the frontiers of stability.

The UK is an associate member of the international **Facility for Antiproton and Ion Research (FAIR).** The UK's involvement is mainly through the NUclear STructure, Astrophysics, and Reactions (NUSTAR) collaboration. NUSTAR enjoys special status among the four pillars of FAIR, being the first user of the new facility (the SuperFRS fragment separator will be ready first), with experiments predicted to start around the end of 2027. The UK has provided equipment such as the AIDA implantation and decay array and the FATIMA $LaBr_3$(Ce) fast-timing array for DESPEC (Decay Spectroscopy); the target-recoil detector for R^3B (Reactions with Relativistic Radioactive Beams) (an ongoing STFC project); CARME (part of the STFC-funded ISOL-SRS project) for CRYRING (part of APPA, which stands for Atomic, Plasma Physics and Applications); LYCCA (with Sweden) and significant contributions to AGATA, the γ-ray tracking array that will be used as part of HISPEC (High-resolution in-flight spectroscopy).

NUSTAR has over 630 registered scientists, including approximately 420 senior members with PhD degrees (excluding those from Russia). Of these, 9% are from the UK, the second largest community after Germany.

The aforementioned detector systems are at the core of the different experimental setups, underpinning UK leadership in the addressed science and individual experiments.

In R^3B, the UK target-recoil detector provides unique possibilities to study elastic, inelastic and quasi-free scattering, knockout and breakup reactions. The UK leads experiments on deuteron quasi-free scattering reactions and also studying short-range correlations.

All decay spectroscopy experiments have AIDA at their core, with the majority of experiments also using FATIMA. The UK has leadership in experiments addressing physics at the extremes on both the proton- and neutron-rich sides of the nuclide chart. Examples are related to seniority ($N=50$, $Z\sim82$), prolate-triaxial-oblate shape evolution around ^{190}W, and the neutron-rich $N\sim126$ region that through its link to the r-process has astrophysical interest. Both AIDA and FATIMA are used at other facilities as well: AIDA was a key element of the highly successful BRIKEN collaboration at RIKEN to study β-delayed neutron emission for the most neutron-rich nuclei produced to date; the 36 FATIMA detectors will be included in the IDATEN array, within a campaign which presently has 9 approved experiments at RIKEN, starting from 2024.

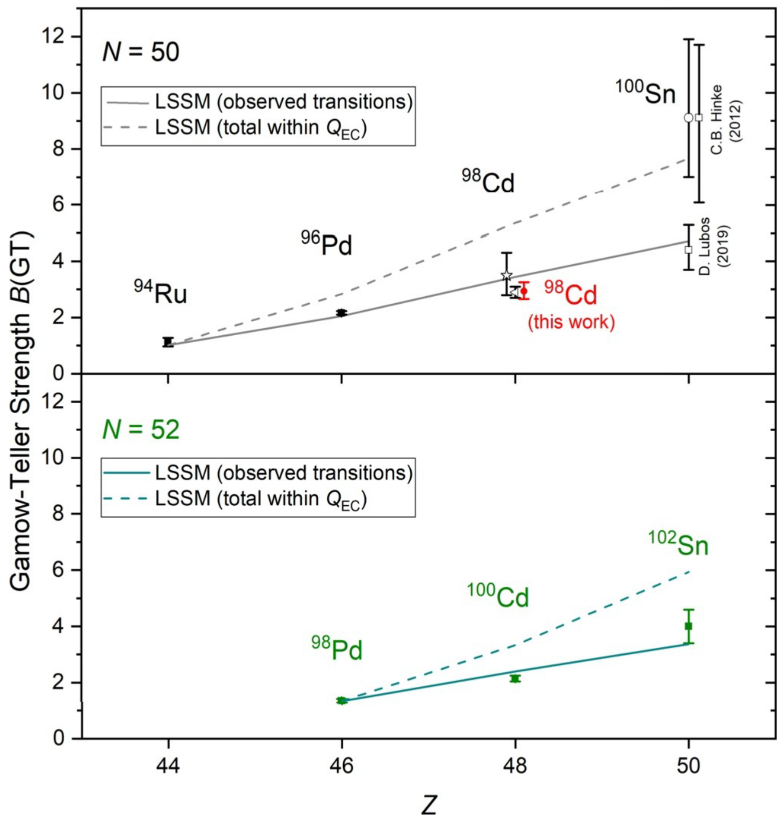

Figure 14: The Gamow-Teller strength B(GT) for ($0^+ \longrightarrow 1^+$) transitions for even-even N=50 isotones (top panel) and N=52 isotones (bottom panel). Direct mass measurements of neutron-deficient nuclides around the shell closure below ^{100}Sn were performed at the FRS Ion Catcher (FRS-IC) at GSI. Reproduced with permission from Ali Mollaebrahimi *et al.*, Phys. Lett. B **839**, 137833 (2023).

HISPEC and DESPEC occupy the same physical space at GSI and FAIR, therefore they run in campaigns. Presently DESPEC experiments are ongoing, the next HISPEC campaign is envisaged after construction of FAIR is completed, employing the new SIS100 synchrotron and Super-FRS.

Nuclear reaction experiments at the CRYRING all rely on the newly commissioned CARME silicon array. The science focus is the study of nuclear reactions of astrophysical interest using direct and indirect methods. The stored beams of CRYRING uniquely provide the opportunity to study low-energy reactions with radioactive ions (produced by fragmentation) interacting with a pure, cryogenic gas target. Three further, high priority, UK-led experiments were approved by the GSI G-PAC in February 2024 including measurements that could be a transformative step forward to understand the long-standing issue of electron screening and its impact on reaction rates in the quiescent burning phase of stars.

The NUSTAR SHE sub-collaboration focuses on the study of superheavy elements through chemical studies, reaction studies, structure studies, mass measurements and atomic property measurements. It utilises the TASCA and SHIP separators behind the UNILAC, and the TASISpec, Lundium and SHIPTRAP setups. The collaborators from the UK contribute mainly to the nuclear structure and chemical investigation, as well as laser spectroscopy of the heaviest atoms.

The **Radioactive Ion Beam Factory (RIBF) at RIKEN** has been a world-leading facility for the production of fast-moving rare isotopes and, since its introduction in 2006, has led the discovery of about 200 new isotopes with some notable cases including the production of ^{140}Sn and the potentially doubly magic ^{60}Ca. It delivers intense beams of about 4,000 unstable nuclei, ranging from hydrogen to uranium, and has enabled the study of some of the most exotic nuclear systems beyond the drip line, such as the unbound ^{28}O and the correlated four-neutron system. Characterisation of such isotopes, and other doubly magic candidates such as ^{78}Ni and ^{100}Sn, is currently at the forefront of experimental nuclear structure research. γ spectroscopy near the drip lines is often performed using the high-efficiency DALI2$^+$ array. A new higher-sensitivity γ-ray spectrometer (HYPATIA) has been identified as a top priority for the RIBF and was endorsed by the RIKEN PAC in Autumn 2023. The UK has a leading role in the development of this new instrument for RIBF by employing novel scintillator technology. The RIBF facility has also enabled studies of the trans-actinide elements, isomer experiments and many other high-resolution nuclear spectroscopy experiments with e.g. the EURICA and HiCARI arrays. Mass measurements, decay spectroscopy (γ-ray detectors and β-delayed neutron detection), Coulomb excitation, and secondary fragmentation are also very active programmes. The UK is strongly involved in many of these experimental activities, with high visibility and leadership roles in the experiments and the collaborations.

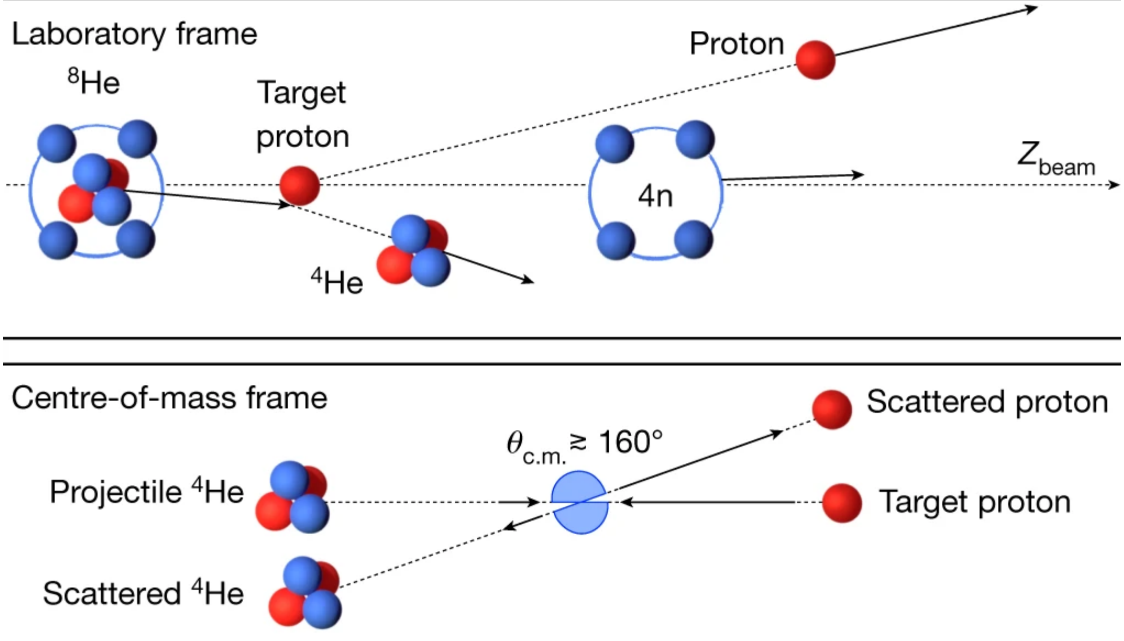

Figure 15: Top: quasi-elastic scattering of the ^{4}He core from a ^{8}He projectile off a proton target in the laboratory frame. Bottom: the equivalent p–^{4}He elastic scattering in their centre-of-mass frame. Experiment performed at RIKEN. Reproduced with permission from M. Duer *et al.*, Nature **606**, 678 (2022).

Experimental campaigns and new instruments are approved in a highly competitive process by the RIKEN PAC, which is carried out yearly and is open to all researchers worldwide. The UK community is commonly awarded a considerable fraction of the available beam time at the RIBF facility and many UK PhD theses over the past decade have been based on data from these RIBF experiments.

Stable beam facilities

The **Argonne Tandem Linear Accelerator System (ATLAS**) is the world's first superconducting accelerator for heavy ions at energies close to the Coulomb barrier. ATLAS remains a world-leading facility for experiments with high-intensity heavy-ion beams, with the possibility of accelerating all elements between hydrogen and uranium to energies up to 17 MeV/u. Beams are delivered to one of three target areas for a wide variety of experiments focussed on nuclear structure and reactions, totalling around 8000 hours of beam time delivered per year. The ongoing Multi-User upgrade of the facility will enable ATLAS beams to be delivered to more than one experiment simultaneously, significantly increasing the effective number of beam time hours delivered to better serve the large international user community.

The Fragment Mass Analyzer (FMA) remains a key tool for both in-beam and decay spectroscopy at the proton drip line, of relevance for both nuclear astrophysics and structure. However, new possibilities to study the heaviest nuclei have been opened up with the development of the gas-filled separator AGFA as well as the digitisation of the existing detector systems, which allows for novel pulse-shape analysis techniques to be applied and improved count rate capabilities. The HELIOS spectrometer allows measurements of nuclear reactions with excellent charged-particle resolution running in silicon array mode but can also be used with the Active Target Time Projection Chamber to study reactions for both astrophysics and nuclear structure with weak radioactive beams. The ATLAS facility is entering a new period with a broad set of new scientific opportunities offered by the nuCARIBU and N=126 factory, allowing access to the neutron-rich region of the nuclear chart below ^{208}Pb, which is critical for understanding the last abundance peak in the rapid neutron capture process. In addition, the continued development of in-flight radioactive beams (RAISOR) enabling direct studies of nuclear reactions for structure and astrophysics, such as the (α,p) and (p,α) reactions to investigate breakout into the rp-process, for example.

The UK nuclear physics community is strongly involved in other stable beam facilities such as, JYFL, GSI and LUNA which are discussed elsewhere in this document.

Neutron-beam facilities

The spallation neutron source **n_TOF at CERN** is a unique facility to measure neutron-induced reactions providing a high instantaneous neutron flux, low duty cycle, high resolution and low background with neutron energies spanning over 10 orders of magnitude. The n_TOF collaboration is operating three experimental areas for neutron time-of-flight (EAR1 and EAR2) and activation measurements (NEAR), and currently consists of 132 scientists from 40 institutions, with 3 teams from the UK (Edinburgh, Manchester and York). UK scientists have played leading roles in the development and exploitation of the facility, with support of prestigious ERC funding (Edinburgh). UK members have acted as spokespersons for many individual experimental campaigns (in 2023, for example, 20% of the time-of-flight beam time were UK-led nuclear astrophysics measurements), and have led the development of new detection systems (e.g., silicon telescope system and fission fragment spectrometer).

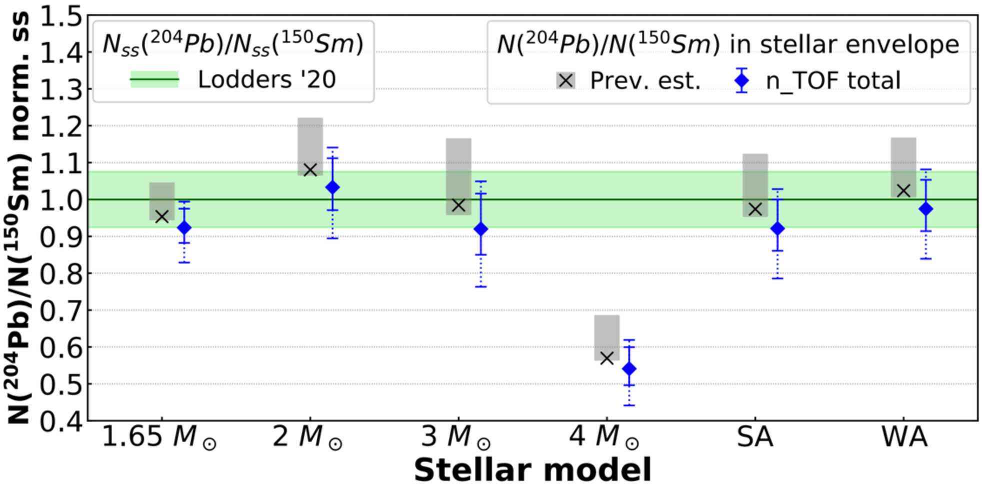

Figure 16: Isotopic abundance ratios (^{204}Pb)/(^{150}Sm) in the star envelope at the end of the AGB phase, obtained using the Maxwellian-averaged cross sections measured at the CERN neutron time-of-flight facility n_TOF. All values are normalised to the solar system ratio, which is highlighted by the thick green bar with the green shaded band depicting its uncertainty. Reproduced with permission from A. Casanovas-Hoste *et al*. Phys. Rev. Lett. **133**, 052702 (2024).

At present, the **reactor at Institut Laue Langevin** (Grenoble, France) presents experimentalists with the most intense continuous flux of thermal neutrons. A role that in the mid-term will be taken over by the **European Spallation Source** (Lund, Sweden). The experimental setup at the fission-fragment separator Lohengrin and the fission product prompt γ-ray spectrometer (FIPPS) provide the optimal facilities to study fission processes and their final product nuclei. UK scientists have strong involvement in nuclear reaction and structure studies of fissioning nuclei and their fragments. UK scientists have also initiated collaborations and led measurements at the neutron time-of-flight and tandem accelerator neutron sources of the Joint Research Center (Geel), which allows high precision studies of interest to nuclear technologies and astrophysics.

UK-based facilities

The **National Physical Laboratory** (NPL) is the UK's National Metrology institute and has national responsibility for traceable measurement of radioactive material, including traceability to the SI unit of the becquerel (Bq). NPL holds the UK primary and secondary standards for radioactivity, providing the first line of traceable measurement for more than 100 different radioisotope species. These are linked to the international measurement system (the SI) and provide a route to demonstrate that measurements of radioactive materials are accurate, internationally consistent and independent. Primary standardisation techniques include Defined Solid Angle α counting; Triple-to-Double Coincidence Ratio and other coincidence methodologies depending on the nature and details of the decay modes of the radionuclide under investigation.

A significant part of the NPL's work is involved in determining precise values for reaction and decay properties of radionuclides, such as decay half-life and γ-ray emission probability. These underpin the standards produced and are needed for precise instrument calibration, which is key for wider applications of nuclear measurements. These parameters find particular impact in the national impact themes of Energy and Environment, Health, and National Security & Resilience. Much of the group's effort is focused on establishing coherent datasets and standards that are accepted internationally. Information on the calculation of uncertainties is often limited and there is little information on the experimental methods used. NPL is involved in a number of nuclear data evaluation projects, which is the process of collating data from published measurements and taking into account knowledge of the physical processes to determine recommended values with uncertainties for the key parameters.

High quality nuclear reaction and decay data are also crucial in the design of Generation IV reactors. NPL-based national sovereign facilities are used to measure neutron-induced fission cross sections on actinide targets, as part of the work to reduce uncertainties in nuclear data related to fast reactors. The neutron fluences delivered during these measurements are established to high precision, so the reaction cross sections are measured directly. This is advantageous as most measurements are made relative to other cross sections, which introduces higher uncertainties.

The NPL houses a range of other national facilities and measurement infrastructure to carry out its mission to realise measurements of radioactive materials which are traceable to the becquerel. In addition to the dedicated neutron facility; radioactive standards for low-background measurements of noble gases which are crucial for real-time evaluations of reactor criticality and nuclear weapons monitoring, radiochemistry suites for highly sensitive separations of chemically-different radioactive sources created in the same reactions, and a range of digital-based counting instrumentation for nuclear decay parameter measurements, including the National Nuclear Array (NANA) of fast-timing γ-ray scintillator materials. This instrumentation development, together with the intellectual capital available from the NPL-based scientists also allows collaboration in more longer-horizon nuclear structure and astrophysics measurements at international facilities such as FAIR, IJC-Orsay, CERN-ISOLDE and ILL-Grenoble in collaboration with the UK academic nuclear community in particular through contributions to dedicated γ-ray spectrometer arrays such as NuBALL, FATIMA and STELLA.

3.2 Hadron Physics

International electron accelerator facilities currently in use by UK nuclear physics for hadron physics comprise JLab, the Mainz Microtron and Bonn, with **Jefferson Lab (JLab)** being the world's premier facility for hadron physics study. JLab houses CEBAF, the continuous electron beam accelerator facility, a high-intensity polarised electron accelerator offering unparalleled luminosities. When this accelerator is coupled with the high resolution and/or large acceptance detector systems in the different experimental Halls of JLab (A, B, C and D), this offers a unique control over all relevant degrees of freedom and a precise determination of the initial and final states in hadron physics investigations. Halls A and C at JLab operate at the forefront of the world's high luminosity frontier for hadron structure studies in the valence regime with high resolution, Hall B offers a large acceptance detector for hadron structure and spectroscopy studies, with the electron scattering programme complemented by a quasi-real photon beam programme which is underpinned by the UK Forward tagger. Whilst Hall D converts the electron beam into a real photon beam for high-resolution spectroscopy studies with the large acceptance Glue-X detector. In the future, Hall D will host the neutral Kaon beam facility, with the unstable beam generated from a new Compact photon source. User access to JLab is under a Memorandum Of Understanding and/or a Non-Proprietary User Agreement. Jefferson Lab is expected to undergo two upgrades within the next decade. First will be to add the capability for a positron beam and, secondly, discussions are underway for a subsequent energy upgrade of the electron beam from 12 to 22GeV.

In the future, new opportunities for hadron physics will arise from the **Electron-Ion Collider (EIC)** that will be built at Brookhaven Lab in the USA within the next decade. The EIC is an upcoming first-of-its-kind facility that will collide polarised electrons with polarised protons/light ions, as well as a full range of unpolarised heavy ion species. Covering a wide range of centre-of-mass energies and with high luminosities (for a collider) reaching $10^{34}cm^{-2}s^{-1}$, the EIC will unlock a new kinematic regime for hadron structure, enabling a mapping of 3D and inclusive structure in the gluon-sea, low-x region, with unprecedented precision, as well as the possibility to probe gluon saturation.

The unique physics capabilities of the facility for hadron studies, as well as the detector requirements, have been laid out in the EIC Yellow Report (2021), produced by the international community and with significant UK involvement and leadership. The fully hermetic detector design, developed by the newly formed ePIC Collaboration, will allow measurement of all final state particles. Instrumentation in the far-forward and far-backward directions is additionally aimed at fully exclusive reconstruction of diffractive processes and photoproduction, respectively. The design and construction of several of the ePIC detector sub-systems are led by the UK.

The EIC experimental programme is highly complementary to the measurements currently being conducted in the valence and sea-quark regimes at JLab and COMPASS at CERN. Some of the main topics to be studied by the EIC include: the mechanisms by which the mass of nucleons, and consequently the bulk of the mass of all the visible matter in the universe, is generated, the origin of the internal angular momentum or spin of nucleons, and the emergent properties of matter driven by densely packed gluons. Examples of planned reactions to study these topics include inclusive DIS, SIDIS, TDIS and hard exclusive reactions, like DVCS, TCS and deeply virtual meson production. Extending the energies significantly beyond what is available at JLab also opens the possibility of spectroscopy of charmonium and bottomonium systems, providing unique possibilities for hadron spectroscopy.

Heavy ion collisions at the LHC are also used by **ALICE** physicists in the UK. 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, which is underway by the ALICE collaboration at CERN. In ALICE, the collisions of ions at high energies addresses the collective properties of strongly interacting matter in terms of the phase equilibria and their discernment in terms of QCD degrees of freedom. UK institutions have contributed heavily to the ALICE detector system and are well positioned to lead contributions for a future **ALICE 3**.

In the **CERN North Area (NA)** protons from the SPS impinge on a target system to provide secondary and tertiary beams of charged pions, Kaons, protons and muons as well as their anti-particles to fixed target experiments in an array of experimental halls. UK activity is via AMBER/NA66 and focussed on a vertex detector for hadron radius measurements, with potential future engagement in beam monitoring equipment for Drell Yan- and hadron spectroscopy measurements, as well as particle identification detectors for spectroscopy (complimenting existing EIC efforts in the UK). Beam time is competitively allocated and access is granted through the AMBER/NA66 collaboration as part of the general UK contribution to CERN.

3.3 Digital Research Infrastructure

Theorists and experimentalists alike make use of computing and data facilities of various sorts as part of their research. Whether for data analysis or for exploiting theoretical models, or other uses, facilities associated with nuclear physics laboratories, with Universities, or stand-alone national-level facilities are a necessary part of the UK nuclear physics programme. ALICE makes use of the Worldwide LHC Computing Grid (WLCG) and in particular, through the GridPP project, the UK contributes to this. It could be that the EIC will also use GridPP.

STFC Facilities

STFC supports digital research infrastructure through the top-level IRIS project that supports the DiRAC High Performance Computing (HPC) facilities, GridPP, which provides large-scale data storage and processing primarily for particle physics experiments, but including the JLab programme discussed elsewhere in this document, as well as coordinating access and collaboration within the community. Members of the UK nuclear physics community are active on the IRIS delivery board ensuring nuclear physics interests are heard.

DiRAC itself is distributed across various sites depending on specialised hardware capabilities: Data-Intensive-at-Leicester (DIaL) and Data-Intensive-at-Cambridge (DIaC) which are general purpose systems, the extreme scaling system at Edinburgh, which caters for CPU-intensive applications with high data throughput, and the memory-intensive system at Durham optimised for solving problems that require large amounts of computer memory.

Time on DiRAC systems is granted through a competitive process, in which proposals are submitted and considered by referees and an allocation committee. The UK nuclear physics community makes use of DiRAC in several projects, including reaction and structure theory for low energy nuclear physics and lattice QCD calculations for hadronic physics.

DiRAC has evolved as computational hardware and software technology develops, and this development continues, with upgrade and development plans led by a combination of practical technology and user needs to reach desired physics goals. UKRI have recently conducted a survey of user needs for large-scale computing infrastructure, to which community members were able to contribute. Access to DiRAC hardware, and research software engineers, will continue to be vital to the UK nuclear physics community. As hardware develops and hence the DiRAC architecture evolves to, e.g., more GPU-based computing, the ability to collaborate and access expertise to efficiently port or develop codes to exploit the hardware is vital. Funding streams such as eCSE, directly from the computational facilities in the UK, is a welcome method to directly access such expertise.

Quantum Computing

Quantum computing is an emerging technology holding the prospect of a revolutionary new way to attack many problems through algorithmic means. Allied to the wider field of quantum technologies, quantum computing holds particular promise for simulation of many-body quantum systems such as nuclei whereby the basic processing units of a quantum computer (qubits or similar units) are prepared in such a way so that the many-qubit wave function serves as a proxy for the many-body wave function of interest. By appropriate querying or manipulation of the quantum computer, observables for one’s system of interest, such as an atomic nucleus, can be extracted. UK work in this area makes use of simulated quantum computers on classical hardware, including DiRAC, and open-access hardware from IBM. Those working in this area are well placed to exploit UK national facilities that are developed as part of the UK National Quantum Computing Centre (NQCC). Quantum computing is likely to be a rapidly changing field in coming years, and nuclear physicists exploiting this technology will need to navigate the technology landscape. The ability to access national-level facilities will make this job easier and allow the leveraging of greater computational power.

4. UK International Leadership

The UK leads or plays a major role in numerous projects across various areas of nuclear physics, nuclear astrophysics and hadron physics, encompassing both experimental and theoretical perspectives exploiting the substantial skill base in technology development within the UK. Through these projects, the UK provides significant in-kind contributions to international experiments through the provision of equipment that advance the physics capabilities at these facilities. This gives UK nuclear physicists significant buy-in to international facilities and leadership in the physics programmes.

4.1 Leadership Roles

The role of UK physicists in leading international science is evidenced generally through scientific output and in the leadership roles they hold. UK scientists have many official leading roles in international accelerator laboratories, like CERN and GSI/FAIR. Similar roles do not exist in nominally national facilities. Nevertheless, UK scientists are driving the physics through STFC-funded projects in facilities such as FRIB, RIKEN/RIBF, JYFL, Legnaro and JLab, amongst others. UK physicists have recently held or currently hold several prominent positions within international nuclear and hadron physics research programmes, including:

- ISOLDE Collaboration Spokesperson.
- CRIS (Collinear Resonance Ionization Spectroscopy), IDS (ISOLDE Decay Station) and ISS (ISOLDE Solenoidal Spectrometer) Spokespersons.
- Several roles within the AGATA collaboration (e.g., chairs and members of the AGATA Steering Committee, chair and members of the AGATA Management Board, chair of the AGATA Collaboration Council, AGATA campaign Spokespersons, AGATA Working Group leaders and AGATA Team leaders).
- Member of the Joint FAIR/GSI Scientific Council.
- NUSTAR (Nuclear Structure, Astrophysics and Reactions) Collaboration Spokesperson.
- Spokespersons for Laser Spectroscopy and Superheavy Elements for the NUSTAR collaboration.
- Significant community leadership at TRIUMF, including 3 out of the current 7 members of the TRIUMF User Executive Committee (TUEC) and 2 of the 3 TUEC chairs.
- ALICE Collaboration Board chair; Trigger co-ordination & Physics Board member; Physics Analysis Group co-ordinators for Strangeness, Jet-Photon Studies and Heavy flavour semi-leptonic decays; System run coordinators for ITS and CTP; Editorial board members; Management board members.
- JLab Users Organisation Board of Directors members at large.
- JLab Hall B CLAS Collaboration Hadron Spectroscopy Working Group Chair, Membership Committee member, Charter and By-laws Committee member.
- JLab Halls A and C Collaboration User Board.

JLab Hall A SBS Coordinating Committee members

ePIC Collaboration Exclusive, Diffractive and Tagging Working Group co-convenor; Low-Q2 (High Rate Tracker) - Detector Subsystem technical coordinator; Far-Forward/Far-Backward Cross Cutting Working Group convenor; Far Backward Working Group convenor; User Learning Working Group co-convenor; liaison to the Users Learning Working Group for the Reconstruction Working Group; ePIC Collaboration Council institutional representatives.

LEGEND collaboration simulations and analysis Coordinators; LEGEND collaboration Steering Committee; Level-2 lead of the LEGEND-1000 international project.

Two members of the delivery board of the IRIS digital research infrastructure project.

R^3B Management Board member and Scientific Director.

Members of the community are often invited on the basis of their scientific expertise to sit on Programme Advisory Committees to give advice on the operation and physics programmes of international facilities. There are currently UK members on the advisory bodies for:

ISOLDE and n_TOF at CERN (Switzerland)
ATLAS at Argonne National Laboratory (USA)
Facility for Rare Isotope Beams, FRIB (USA)
Accelerator Laboratory, University of Jyväskylä (Finland), including Chair.
RIKEN (Japan)
GANIL (France)
GSI (Germany)
ALTO, Orsay (France)
RAON, Institute for Basic Sciences (South Korea)
ISAC, TRIUMF (Canada)
RCNP (Osaka, Japan).

4.2 Current Projects - Ongoing Involvement and Exploitation

The UK Nuclear Physics community provides support to previously funded projects, primarily through consolidated grant funding and cross-community support.

AGATA

High precision γ-ray spectroscopy is one of the most powerful tools used to study the structure of excited nuclear states, and it has contributed to the discovery of a wide range of new phenomena. Nuclear structure studies far from stability are entering into a high-precision era with the availability of increased intensities and purity of radioactive ion beams, and new methods to produce exotic nuclei using stable beams. AGATA is a key instrument to perform such spectroscopy.

The science that can be addressed with AGATA is wide-ranging and overlaps with many of the research interests in the UK nuclear structure and astrophysics community. This science covers the nuclear landscape to the extremes of isospin towards and beyond the drip lines, to the highest spins close to the fission limit and to the heaviest nuclei. It involves investigating the evolution of shell structure and magic numbers, the interplay between single-particle and collective degrees of freedom, shape coexistence, exotic shapes, nuclear pairing, reaction dynamics and key astrophysical reactions.

The AGATA community recently identified scientific opportunities for the coming decade using a range of reaction techniques and methodologies employed at the current and future European facilities. In particular, the capabilities of AGATA using fusion-evaporation reactions, Coulomb excitation and transfer reactions, multi-nucleon transfer reactions and in-beam spectroscopy with fragmentation beams represent valuable opportunities for UK-led science with AGATA.

ISOL-SRS

The ISOL-SRS project has successfully completed the construction and commissioning of two spectrometers designed for precision measurements of charged particles emitted in nuclear reactions induced by radioactive ion beams.

The internal spectrometer, known as the CRYRING Array for Reaction Measurements (CARME), utilises a double-sided silicon strip detector array with application-specific integrated circuit (ASIC) instrumentation, developed initially for the AIDA array. CARME detects charged particles at forward and/or backward laboratory angles at GSI/FAIR and focuses on studying nuclear reactions of astrophysical interest using both direct and indirect methods. CARME was successfully commissioned in February 2022, with its first science experiment scheduled for February 2023, demonstrating the study of charged particle resonances with very high CM energy resolution. Future studies envisage the measurement of astrophysical reactions using a high-intensity, transverse proton beam, measurements that could be a transformative step forward to understand the long-standing issue of electron screening and its impact on reaction rates in the quiescent burning phase of stars.

The external spectrometer, the ISOLDE Solenoidal Spectrometer (ISS), is based on the novel helical orbital spectrometer concept and takes radioactive beams directly from HIE-ISOLDE at CERN. The ISS array also features a double-sided silicon strip detector array with ASIC instrumentation, developed for the R^{3}B project, to detect charged particles transported in the magnetic field of a 4T superconducting solenoid, previously used as a hospital MRI magnet. ISS was successfully commissioned in 2021 and its science programme includes studies of light nuclei, probing evolving shell structure, measuring reactions pertinent to nuclear astrophysics and using reactions to probe nuclear fission in exotic nuclei.

AIDA

The Advanced Implantation Detector Array (AIDA) delivers one of the key detector systems for GSI/FAIR, a double-sided silicon strip detector array with ASIC instrumentation. AIDA detects the implantation of very high-energy, highly-exotic nuclei, and their subsequent low-energy radioactive decays. The array is essential to the success of one of the cornerstones of the GSI/FAIR science programme: the study of the structure and properties of the heaviest, very neutron-rich nuclei on the r-process path.

AIDA was a key element of the highly successful BRIKEN collaboration, to study β-delayed neutron emission for the most neutron-rich nuclei produced to date at the Radioactive Ion Beam Facility (RIBF), RIKEN. It has now been commissioned at GSI/FAIR as part of the phase 0 science programme.

Additionally, AIDA is utilised by the Lund York Cologne charged-particle array (LYCCA) for HISPEC at GSI/FAIR and the CRYRING Array for Reaction Measurements (CARME) for experiments at CRYRING, GSI/FAIR. AIDA leverages world-class UK technical capabilities to deliver detector systems which provide opportunities to lead world-class science programmes at the leading international accelerator facilities.

HISPEC/DESPEC

HISPEC/DESPEC is the collaboration aiming to utilise spectroscopy to study the structure of exotic nuclei as part of the NUSTAR collaboration at FAIR. It employs both decay spectroscopy (DESPEC) and fast beams (HISPEC). In its standard configuration, DESPEC is based on the AIDA implantation and decay array and the FATIMA $LaBr_3$(Ce) fast-timing array, both constructed in the UK, and is further enhanced by a high-resolution HPGe array.

In addition to GSI/FAIR, FATIMA detectors have been employed in experiments at Argonne, RIKEN, Orsay, Warsaw and JYFL. Starting in 2024, all 36 FATIMA detectors will be integrated into the IDATEN array at RIKEN. Experiments at both GSI/FAIR and RIKEN aim to unravel the structure of the most exotic nuclei currently experimentally accessible on both sides of the stability line.

The HISPEC setup features the AGATA array, in which the UK plays a significant role, as its core component. The identification of reaction products is facilitated by LYCCA, a system developed through UK-Swedish collaboration. The next HISPEC campaign is envisaged to take place with beams delivered by the SIS100 and SuperFRS complex, currently under construction.

DEMAND

The UK-led Direct Experimental Array of Neutron Detectors (DEMAND) project, has pioneered a new technique for the direct measurement of inverse kinematic (α,n) reactions, which are crucial for nuclear astrophysics. These reactions significantly influence the chemical evolution of our Galaxy, particularly through their dominant role in weak r-process nucleosynthesis. Studying these reactions on unstable nuclei presents a key experimental challenge for nuclear physics research, necessitating measurements in inverse kinematics and requiring the detection of resulting neutrons.

The DEMAND project constructed a neutron detector array using detectors made of organic glass scintillator material, that have a fast-timing response, high light output, and are capable of excellent n/γ pulse shape discrimination. This array was recently coupled to the DRAGON recoil separator at TRIUMF and successfully commissioned with a pioneering, first inverse-kinematic direct measurement of the astrophysically important ^{22}Ne(α,n)^{25}Mg reaction, expected to be the dominant source of neutrons for the weak s-process. This proof-of-principle study paves the way for a future UK-LED programme of (α,n) reaction measurements with radioactive ion beams. In particular, it is envisaged that a future larger array will be developed for use in conjunction with the EMMA and SECAR spectrometers at TRIUMF and FRIB, respectively.

LUNA

For nearly three decades, the Laboratory for Underground Nuclear Astrophysics (LUNA) has been the world-leading facility for studying low-energy reactions of astrophysical significance underground. Recent findings from LUNA on the destruction of deuterium during Big Bang Nucleosynthesis have resulted in a baryon density that aligns more closely with independent analyses of the cosmic microwave background, thereby reinforcing the standard cosmological model.

At LUNA, the main neutron source reaction ^{13}C(α,n)^{16}O, was studied at astrophysically relevant energies for the first time. The new reaction rate derived from this study directly impacts the nucleosynthesis of s-process nuclei, including radioactive ^{60}Fe and ^{205}Pb, which were present in the early solar system. Upcoming reaction studies at the LUNA 400kV accelerator will focus on the study of reactions significant for understanding solar metallicity, the O-Ne anticorrelation observed in the spectra in globular clusters, and isotopic anomalies observed in pre-solar grains.

At LUNA, the UK is leading a range of activities with ERC support specifically aimed at addressing puzzling abundance anomalies in Globular Clusters, the origin of CNO nuclei in first stars, and the cosmological lithium problem. With the new ‘LUNA MV’ accelerator recently installed underground and the availability of α and carbon beams over wide energy ranges, further major advances are also expected in our understanding of helium- and carbon-burning stages in the evolution of massive stars.

The future scientific programme at the LUNA 400kV accelerator anticipates robust UK leadership and involvement. Additionally, a new 3.5MV accelerator, the Bellotti Ion Beam Facility (Bellotti IBF), has recently been installed at Gran Sasso in Italy, promising unprecedented opportunities for underground studies of helium- and (uniquely worldwide) carbon-burning reaction studies. The scientific programme at this new facility has just begun with the measurement of the ^{14}N(p,γ)^{15}O reaction important for the core metallicity of the Sun. This study will be followed by cross-section measurements of the ^{22}Ne(α,n)^{25}Mg reaction, the secondary neutron source for the weak component of the s-process, and the ^{12}C+^{12}C fusion reactions, important for the late evolution of massive stars.

JLab

The UK successfully designed and constructed key equipment for both Halls A and B of JLab. In Hall-B the Forward Tagger apparatus provides accurate track and energy reconstruction for the electrons which scatter at small angles to the beamline (5-12 degrees). It is now baseline equipment for CLAS12 and operates successfully in a region having the highest particle flux and radiation dose for any detector sub-system in CLAS12. The small angle scattered electron events underpin the CLAS12 quasi-real photon beam physics programme. This includes UK led aspects such as spectroscopy of doubly strange baryons and searches for exotic hybrid mesons in the light quark sector. As well as its use for electrons, the detector is the basis for detection of all other particle types in this important forward angular region of CLAS12. Hall A efforts were focussed on the SBS programme to measure primarily the Sach's electromagnetic form factors of the nucleon at high Q^2, as well as additional future structure topics such as SIDIS and meson structure. The UK has played a leading role in this programme, via spokesperson roles, on-going form factor analyses and hardware contributions. The UK designed, manufactured and installed fast front-end electronics (amplifier/discriminator readout cards based on the NINO ASIC) for several subsystems in the SBS experiments, as well as constructing a timing hodoscope for measuring scattered electrons in the SBS experiments.

4.3 New Projects

FAUST

Institutions: 3	Academics: 6	Project value: £3.4M

The FAUST project aims to develop an advanced array combining silicon and scintillator detectors to be used with in-flight radioactive ion beams in front of the S800 magnetic spectrometer, and coupled with the GRETA γ-ray tracking array. FAUST will be deployed at FRIB at Michigan State University, which provides the widest range of intense radioactive ion beams, both in-flight and reaccelerated. FRIB beams will be used both for nuclear astrophysics and for nuclear structure studies.

FAUST will provide charged particle detection capabilities with high angular and energy resolution across most angles, enabling the study of transfer and other scattering reactions induced by ^{1}H and ^{2}H target nuclei. The FAUST array is designed for high-energy particles from in-flight beams and will exploit digital electronics consistent with established FRIB standards. This device will allow for the study of very high-energy, light charged particles in conjunction with γ rays, thereby providing the means to extract key properties of astrophysical resonances and reaction cross sections.

This project will enable the UK to contribute to developments at FRIB and to lead transfer reaction studies addressing crucial nuclear astrophysical reactions on proton-rich nuclei involved in explosive hydrogen burning. Additionally, the extensive reach into neutron-rich beams will facilitate cutting-edge studies of single-particle structure that will identify shell evolution and the important associated implications for nuclear structure.

γRIBF-UK

Institutions: 4	Academics: 5	Project value: £2.84M

The γRIBF-UK project aims to construct part of the next-generation scintillator-based high-resolution γ-ray spectrometer, HYPATIA (HYbrid Photon detector Array To Investigate Atomic nuclei), to be used at RIBF at the RIKEN Nishina Centre (RNC) in Japan. HYPATIA will employ a combination of HR-GaGG and $CeBr_3$ scintillators, offering higher efficiency, improved energy and time resolution, and superior peak discrimination capabilities compared to the $DALI2^+$ spectrometer it will replace.

HYPATIA is envisaged to be employed at different experimental stations within the upgraded RIBF facility and its magnetic spectrometers (ZeroDegree, SAMURAI, SHARAQ), each with different performance requirements and constraints. Key future experiments at the RIBF, conducted at intermediate energies, will involve inelastic scattering on high-Z targets to induce Coulomb excitation, as well as inelastic scattering and quasi-free (p,2p) and (p,pn) reactions on a liquid hydrogen target. Through the γRIBF-UK project, the UK will play a leading role in the construction of the HYPATIA array and the world-class research it will perform at the RIBF.

R^3B–TRT

Institutions: 2 Academics: 3 Project value: £2.9M

The R^3B-TRT project will construct the new Target Recoil Tracker (TRT) for in-beam experiments with the Reactions with Relativistic Radioactive Beams (R^3B) experimental setup at GSI/FAIR in Germany. Utilising the silicon pixel-based sensor technology developed by the ALICE collaboration, (ALPIDE - ALICE Pixel Detector), and using relevant UK expertise, the R^3B-TRT project will deliver a device with unprecedented position resolution, low material budget and high-rate multi-hit capability.

The UK's primary contributions include the production of 60 modules, each consisting of nine ALPIDE sensors arranged in a linear configuration, and creating the detailed mechanical design to assemble the modules into a multilayer barrel-shape device. The R^3B-TRT device is anticipated to be operational for the first FAIR physics experiments using the R^3B setup and the Super-FRagment Separator (SuperFRS) in 2027.

Looking beyond this initial phase, an upgrade of the R^3B-TRT inner layer is planned. This upgrade will take advantage of the 65nm MAPS sensor technology being developed for ALICE-ITS3 and the MAPS tracker inner layer at EIC, aiming to further reduce the critical inner-layer material budget and reach the optimal angular resolution for the device.

5. Future Opportunities

The international landscape of nuclear physics is constantly evolving, necessitating proactive engagement from the UK Nuclear Physics community to maintain and strengthen its leadership position. Several facilities are currently undergoing upgrade programmes, and new facilities are on the horizon. The UK can cement its leadership by engaging early in large international projects and delivering state-of-the-art experimental equipment, for which our community is renowned. This proactive involvement will secure essential buy-in to facilities and collaborations, ensuring continued influence and innovation in the field.

5.1 Upgrades to Research Facilities and Major Equipment

Nuclear Structure Physics and Nuclear Astrophysics

FRIB400 Upgrade

The recently opened FRIB facility at Michigan State University is fast becoming the world's premier fragmentation radioactive beams facility, capable of delivering a myriad of radioactive beam species to multiple experimental areas at energies from ~1–200 MeV/u. However, the tremendous discovery potential of FRIB can be further extended with an energy upgrade of the FRIB accelerator to 400 MeV/u for uranium, and to higher energies for lighter ions. The FRIB400 energy upgrade will double the reach of FRIB along the neutron drip line into a region relevant for neutron-star crusts and will allow the study of extreme, neutron-rich nuclei such as ^{68}Ca. In this light, the case for the FRIB400 upgrade has been made timely by the dawn of multi-messenger astronomy and the detection of gravitational waves and subsequent follow-up observations of electromagnetic radiation.

The FRIB400 upgrade is explicitly mentioned in the executive summary of the 2023 US Nuclear Science Advisory Committee Long Range Plan, following Recommendation IV, which calls for investments in additional projects and new strategic opportunities that advance discovery science. A key detection instrument for the FRIB400 programme is the future High Rigidity Spectrometer (HRS). The US-DoE has already awarded $115M of funding to develop this device, and it is expected that the current UK-led FAUST silicon array could be adapted to be used in conjunction with the HRS system as part of a future initiative.

ARIEL and the TRIUMF Storage Ring (TRISR) Project

The highly anticipated ARIEL facility 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 evaluations and r-process nucleosynthesis. The UK has had significant involvement in both scientific and technological developments at TRIUMF, and it is expected that these will continue throughout the ARIEL era. In particular, the science interests of the UK community have strong overlaps with the development of the TRIUMF Storage Ring (TRISR) project for ARIEL.

Neutron capture reactions play a crucial role for our understanding of the nucleosynthesis of chemical elements heavier than iron in our Galaxy. However, direct measurements of neutron capture reactions on short-lived radionuclides of critical importance for the astrophysical r process (responsible for the formation of ~1/2 of all elements heavier than iron) have remained out of reach of existing experimental technologies. Consequently, the TRISR project aims to couple a compact neutron generator to a Radioactive Ion Beam storage ring to resolve this issue. This proposed new facility, which could be installed inside the existing ISAC experimental hall, is anticipated to be operational within the next decade.

FAIR NUSTAR Upgrade

The future FAIR facility in Germany is currently under construction and is anticipated to be the European flagship fragmentation radioactive beams facility over the coming years. In this regard, the NUSTAR collaboration, which includes a number of UK members (including the current Spokesperson), is concerned with the study of NUclear STructure, Astrophysics and Reactions at FAIR. In particular, key research interests of the NUSTAR collaboration relate to the use of beams of radioactive species separated and identified by the Superconducting Fragment Recoil Separator (SuperFRS).

The UK is a major contributor in the design, construction and delivery of experimental equipment for FAIR, including AIDA, FATIMA, a double α detector array, the target-recoil detector for R^3B, CARME, LYCCA, and a new injector trap for the GSI MR-TOF-MS. This equipment has already been employed in experiments at GSI and other international facilities such as RIKEN, GANIL, Orsay, Argonne and JYFL. Based on this expertise and combined 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.

GANIL and SPIRAL-2

The GANIL facility in France is undergoing an extensive upgrade phase. Ongoing and planned developments will deliver a wide variety of high-intensity radioactive and stable beams, a new area for low-energy radioactive beam experiments, and increased capability for the study of superheavy elements, direct reaction studies and direct measurements of astrophysical reactions for explosive nucleosynthesis. The UK has a strong history of nuclear physics involvement at GANIL, and it is conceived that a number of opportunities exist for UK leadership in future infrastructure developments for SPIRAL-2. This is evidenced by recent collaborative talks between UK and French researchers aimed at identifying future prospects for UK nuclear activity at the facility. Through these meetings, four collaborative working groups were identified, which would increase UK contribution to existing and upcoming experimental capabilities at GANIL.

SPES at LNL

The main initiative of INFN Laboratori Nazionali di Legnaro (LNL) facility in Italy is the development of the SPES project (Selective Production of Exotic Species), which aims at the construction of an ISOL facility to produce unstable ion beams for nuclear physics experiments and for research and development activities in the field of radioisotopes of medical interest. Significant progress has been made in the construction of the SPES facility and the UK is in a prime position to exploit the low-energy ISOL beams for decay spectroscopy and precision measurements. Furthermore, the UK could provide unique insight and construction support in relation to the ion source used for the delivery of radioactive beams.

Nuclear Science at the STFC Boulby Underground Laboratory (BUL)

BUL has hosted a number of studies in the search for Dark Matter (e.g., DRIFT and ZEPLIN) and currently hosts the CYGNUS programme. The low-background underground environment at BUL appeals to a broad range of scientific studies, from direct measurements of astrophysical reactions to quantum computing and emerging quantum technologies. Of particular relevance for nuclear science is the BUTTON project, which has been proposed as the initial flagship detector for the Advanced Instrumentation Testbed (AIT). BUTTON will contain 6000 tonnes of target material for antineutrino detection. The primary aim of the project is to demonstrate a new and scalable technology that can be used for nuclear non-proliferation via remote monitoring of nuclear reactors. The baseline design will be sensitive to antineutrinos from a galactic supernova burst. However, the alternative designs may also open up opportunities for CNO-cycle solar neutrinos, and searches for neutrinoless double β decay, for which the UK nuclear physics community can provide considerable expertise.

ISOLDE Improvements Programme (LS3 and RUN 4)

Over the past few years, an improvements programme has been developed to realise some of the potential opportunities identified during a series of “Exploiting the Potential of ISOLDE at CERN” or EPIC Workshops. A package of developments was identified that could be realised during, or shortly after CERN Long Shutdown 3 (2026-2028). These include replacement of proton beam dumps and upgrade of the delivery beam line, allowing an increase in proton intensity and energy. Without investment, today the PSB driver accelerator could supply twice the current intensity of protons and increase the energy from 1.4 to 2 GeV, these are above the limitations of the current beam dumps. This would lead to significant increases in yield for fragmentation and deep spallation products of more than a factor of ten in the most exotic species. There will be a consequent increase in both the capability of the facility, by making new isotopes available for study and by facilitating more detailed studies with higher statistics, and the capacity of the facility by reducing the time needed for some experiments. These improvements will maintain scientific opportunities for a world leading ISOL scientific programme throughout CERN Run 4 (2029-2032) and beyond. It will maintain ISOLDE as one of the most important facilities for the UK throughout the next decade. Upgrading of the UK devices at ISOLDE, for example ISS, CRIS, Miniball and IDS, is therefore a priority and consideration should be given to new instruments.

ISOLDE Development (Post-LS3)

Assuming that the current improvements programme is confirmed this year, the collaboration will start to look forward to further developments to the ISOLDE Facility, where the next available opportunity is during LS4, planned for 2033. This planning is only just beginning, so there is the opportunity for the UK to lead and develop a major project to start in the latter period of the next decade. There are many different possibilities and several of these match well with the expertise of UK nuclear physics or closely allied UK communities such as accelerator physics – for example, construction of a superconducting recoil separator and associated detectors; realisation of an upgrade to the EBIS and Trap for HIE-ISOLDE; and increases in energy for post-accelerated beams.

Looking towards the post-LHC era at CERN, beyond 2040, there is a strong need to maintain proton delivery for several unique world leading non-LHC scientific programmes. This could create an opportunity for a new GeV proton machine and an opportunity for a higher power ISOL facility. It would be important for the UK community to consider this in longer term strategic planning into the 2050s.

n_TOF at CERN

Several upgrades to the facility are already planned for LS3 (2026), for example to extend measuring capabilities to new reaction channels such as transmission (of interest to neutrino detector development) and (n,xn) reactions (for example, for neutron damage studies in future fusion reactors), and to develop new detectors with enhanced sensitivity allowing the measurement of even smaller sample material. UK scientists will be strongly involved in these upgrade activities and are developing science cases post LS3 (for example, unveiling the astrophysical origin of nature's rarest stable isotope ^{180m}Ta). The spallation target will reach the end of its lifetime at LS4 (2033), which will open up opportunities for improved target designs yielding higher average and instantaneous neutron fluxes and the construction of additional experimental areas. Additional possible improvements to the infrastructure post LS3 include, the installation of a new measuring station based on a binocular collimation system and background reductions in the experimental areas using Li-doped polyethylene. The collaboration is also exploring the possibility of a complementary activation station at the already approved BDF/SHiP Facility at CERN, which will deliver ultra-high neutron fluxes for activation measurements.

Argonne Multi-User Facility

The Argonne Tandem Linac Accelerator System (ATLAS) is planning an upgrade to a multi-user facility to accelerate both stable beams from an Electron Cyclotron Resonance (ECR) ion source and radioactive beams from an Electron Beam Ion Source charge breeder simultaneously. In this light, it will be possible to run large beam time experiments using CARIBU radioactive ion beams alongside high-intensity stable beam experiments. The UK has a longstanding track record of extensive involvement in the experimental programme at Argonne, and it is foreseen that the UK Nuclear Physics community could play a pivotal role in both developing the future science programme at Argonne, as well as the accelerator facility beam switching infrastructure of the new multi-user facility.

Hadron Physics

Jefferson Lab Upgrades

JLab is currently the world's premier facility for hadron physics and the UK holds several positions of leadership within the JLab scientific community. On-going exploitation of JLab is a key priority of the UK hadron physicists, and UK leadership will continue into future plans for the JLab facility.

In the near-term future, Halls B and D will undergo high luminosity runs - which will expand the existing spectroscopy and structure programmes there. Halls A and C will continue to push the high luminosity frontier, with opportunities for UK physicists to lead instrumentation upgrades and experiments. For instance, the future proposed Solenoidal Large Intensity Device (SoLID) experiment in Hall A will provide opportunities for UK physicists to take on hardware and physics leadership roles. Furthermore, the UK has spokesperson roles on several approved experiments due to run in the future Halls A and C. This includes hadron structure experiments using the BB and SBS setups, which the UK has already invested heavily in. Topics include pion photoproduction and GPDs, as well as meson structure and emergent hadronic mass. In the future, Hall D will host the UK-led neutral kaon beam facility.

JLab is discussing two future upgrades, on a timeline synergistic to preparations for, and overlapping with early running of, the EIC - this is a positron beam and an energy upgrade of the electron beam from 12GeV to 22GeV. Both upgrades would offer UK-based physicists opportunities to lead physics programmes that would be a natural extension of current UK hadron physics activities. There have been white papers published on the physics cases for both upgrades, and the physics cases are still expanding beyond this. These upgrades would be complementary to EIC opportunities.

Operating JLab with polarised and unpolarised positron beams in the future would offer a complementary method for understanding hadron structure via elastic and deep inelastic scattering reactions. For example, measurements with both electrons and positrons would allow for model independent extractions of the electromagnetic form factors, provide more information on two photon exchange effects in electron scattering, and access to gravitational form factors in GPD studies. Dark photon searches could also be expanded. There is a limited kinematic coverage for hadron studies at JLab due to the fixed energy of the 12GeV beam. A future upgrade to 22GeV could offer measurements in a regime bridging the gap between JLab12 (high-x valence quark dominated) and the EIC (low-x gluon dominated). This would be accompanied by the unique capability to perform extremely high precision measurements in this new phase space due to the high luminosities available, which are unavailable elsewhere. Potential topics include new kinematic phase spaces and multi-dimensional binning capabilities for 3D imaging studies, or mid-x (x~0.1) physics like anti-shadowing and the role of the strange sea. Other topics include: better understanding of the interplay between the valence and sea regimes; an increased energy reach far above the J/psi production threshold for studies of the QCD Lagrangian trace anomaly, which is central to the origin of hadron mass; and meson structure studies (for example extended TDIS programmes) to better understand the role of mesons in the nucleon and within nuclei.

ALICE 3

ALICE 3 is a major new and comprehensive detector for the LHC, optimised to carry out an extensive programme to exploit fully the heavy-ion beams for studying the properties of the quark–gluon plasma. ALICE 3 would be able to address a number of key ALICE-physics related measurements that will still be missing after LHC Runs 3 and 4:

- accurate measurements of charm and beauty hadrons, including their correlation over a wide rapidity range, to determine the interactions of heavy quarks of different mass in the temperature range from that of the quark–gluon plasma at the LHC down to that of ordinary matter;
- comprehensive measurements of jet-topological structure and its degrees of freedom, in particular tagged by the localised production of heavy flavour, to probe the transport coefficients of the quark-gluon plasma as a function of temperature and to understand how such coefficients arise from “first-principles QCD”;
- systematic measurements of multiple heavy-flavoured hadrons for which the production from the quark–gluon plasma is expected to be enhanced by orders of magnitude when compared with colour-singlet condensed hadronic matter, providing sensitivity to how the combination of quarks into hadrons depends on the degree of thermalisation;
- comprehensive measurements of the production and behaviour of the charmed exotic states in the quark–gluon plasma and their structure, for example by determining the strong interaction potential between hadrons from measurements of their momentum correlation;
- high-precision, multi-differential measurements of electromagnetic radiation from the quark–gluon plasma to probe its early evolution and thereby probe the restoration of chiral symmetry through the coupling of vector and axial-vector mesons;
- measurements of net-quantum number fluctuations over a wide rapidity range to constrain the susceptibilities of the quark–gluon plasma and to test the realisation of a crossover phase transition as predicted by lattice QCD.

To pursue this physics program, the ALICE Collaboration proposes a novel detector - ALICE 3 - with high readout rate, superb position resolution and excellent tracking and particle identification over a large acceptance, using advanced silicon detectors. It will replace the current ALICE detector and be operational during LHC Runs 5 and 6. The UK is uniquely placed to play a leading role in developments of the outer tracker and trigger due to its unique technological expertise in CMOS MAPS. The UK is experienced in this due to the ITS2 and ITS3 Inner Tracking Systems in ALICE and the EIC silicon vertex tracker.

5.2 Future Projects

The UK Nuclear Physics community has identified numerous projects, which have been endorsed by NPAP. These span all the community’s areas of interest, and also cover aspirational proposals and new initiatives. The proposals listed below have been prioritised by the community and are presented in Chapter 8 of this Roadmap as part of our 10-year plan, together with a proposed timeline.

Proposals within the core STFC PPAN programme remit, listed in order of priority:

Nuclear structure and astrophysics proposals

Low-energy physics at the limits of stability
TRISTAN@ISOLDE
Total Absorption Spectrometer
Production, destruction and studies of heavy elements
Ab initio nuclear theory
Nuclear structure and dynamics with density functional theory
FAIR-UK Low-Energy
FRIB Upgrade
Developments for accessing proton-rich nuclei at the limits of stability

Hadron physics proposals

JLab Future - continued exploitation at JLab and new UK leadership in next generation JLab science
Hadron Physics at AMBER
ELSA@Bonn Project

General community-interest proposals

Photon spallation source
^{160}Gd double β decay
UK centre for quantum entanglement and quantum computing

Aspirational proposals and new initiatives listed in order of priority

Nuclear structure and astrophysics proposals

Enhancing the R^{3}B capabilities at FAIR with a High-Resolution Spectrometer

Hadron physics proposals

ALICE 3

General community-interest proposals

Nuclear Theory Centre
Nuclear Astrophysics Centre
Accelerated Beams for Research and Applications (ABRA) – A National Cyclotron Facility
UK Centre for Nuclear Data
UK Centre for Nuclear Applications
Reactor neutrino flux

Proposals not included in the prioritisation process

The interests of the UK Nuclear Physics community extend beyond the proposals included in the prioritisation process to encompass proposals that do not currently sit well in the existing funding frameworks or are still under development. These proposals are described here and include large-, medium- and small-scale projects, some of which are of cross-community interest. A timeline of the new projects presented in Chapter 4 and current commitments, is presented at the end of this section.

Electron-Ion Collider

The future EIC project will soon represent the state-of-the-art in technology for hadron physics research. This accelerator facility will use high-energy electron beams to reveal insights into the internal structure of protons and nuclei via electron-proton and electron-nuclei collisions.

The UK nuclear physics community has positioned itself as a key international partner in the delivery of the EIC at the Brookhaven National Laboratory in the United States. The project brings together members of the relativistic heavy ion collisions and the electron beam physics communities to address fundamental questions on the origin of hadronic mass, the spin of the nucleon and the properties of dense systems of gluons, amongst other topics. Involvement is currently supported through a UKRI Infrastructure Fund Preliminary Activity that has enabled UK groups to take a leading role in developing some of the key detector technologies that are needed to deliver the science. This includes monolithic active pixel sensors (MAPS) for the silicon vertex tracker, arrays of Timepix4 hybrid silicon sensors for the electron tagger, calorimeter modules for the luminosity monitor and novel active polarised scattering media for scattered neutron polarimetry.

The EIC provides a unique set of capabilities, with corresponding challenges in detector design. In particular, the measurement of low-angle electron scattering reactions requires measurement of the scattered electron co-linear with the re-circling beam. Such energy-degraded electrons can be deflected from the beam's path with subsequent dipole magnets. However, they are still required to be detected very close to the beamline, where rates from background processes are extremely high compared to other parts of the detector. The only practical solution is high-rate pixel tracking detectors, for which the UK has promoted the Timepix4 technology, and now leads the development of this project. Such technology has great synergies with projects in the particle physics community, such as the Velopix detector at LHCb, providing very productive cross-area collaboration.

The EIC project provides a unique opportunity for the UK community to lead the development, implementation, and exploitation of a new major international project. A Full Project bid (£59M) for construction, including a contribution to the accelerator, has been approved by the UKRI Infrastructure Fund. The bid was led by the UK nuclear physics community and brings an equal level of support and participation from the particle physics and accelerator physics communities. The Full Project involves seven universities and two national laboratories. In the international EIC detector collaboration (ePIC), the UK provides the Technical Coordinators of the Silicon Vertex Tracker and Electron Tagger, the Detector Subsystem Leader of the

Far Backward Pair Spectrometer (Luminosity Monitor) and one of the co-convenors of the cross-cutting Far Forward/Far Backward working group. The UK also plays a leading role in developing the future science programme at the EIC and provides co-convenors of the Inclusive Physics working group, and Exclusive, Diffractive and Tagging working group. The UK is also represented on the Executive Board of the detector collaboration, the principal scientific and technical leadership team that provides advice to the Spokesperson's Office. Other on-going EIC-related activities performed outside the UKRI Infrastructure Fund include fast photon sensor developments for the Cherenkov detectors of the EIC.

AGATA

The AGATA spectrometer is now in a phase of advanced development and sustained investment from the international community. As Europe's premier γ-ray spectroscopy project, AGATA is governed by a Memorandum of Understanding (MoU) that commits to creating a 4π device, with an intermediate goal of achieving 3π coverage by the end of 2030. This timeline coincides with the development of various new facilities and capabilities across Europe's accelerator laboratories.

AGATA is currently based at the Legnaro National Laboratory, where it will remain until mid 2028. This will enable the study of the highest priority science cases utilising beams with AGATA coupled to the PRISMA spectrometer and then in a zero degree configuration utilising complementary detectors such as NEDA. The AGATA collaboration has meticulously reviewed the scientific opportunities available in the coming decade, and decided that AGATA will move to GANIL to start a campaign in March 2029 exploiting SPIRAL beams. A formal decision on location after 2030 is to be decided in 2027 once more information on SPES beams at LNL and FAIR timescales become available.

The UK's commitment to AGATA for a 3π spectrometer (135 detectors) up to 2031 is outlined in the MoU covering the period 2021-203. Future capital commitments to a 4π spectrometer (180 detectors) may be requested following this period in parallel with scientific exploitation. For the initial five years of the MoU (2021-2025), the UK has pledged a capital contribution of €1,684k (excluding tax), 97% of which has already been met through the recent STFC AGATA project grant. For the subsequent period (2026-2031), the UK's capital investment is defined as €1,634k (excluding tax). Funding for this second tranche of capital investment has not yet been identified. In addition to capital commitments, the UK is responsible for providing support and maintenance for project components where it holds leadership and ownership. These include mechanics, front-end electronics, detector support and characterisation, experiment simulation, and software tools for pulse-shape analysis, characterisation and analysis. This support will continue to be provided through the consolidated grants and the STFC cross-community teams.

LEGEND-1000

The LEGEND experiment aims to observe a nuclear process in which matter is created without balancing antiparticles, so-called neutrinoless double β decay (NDBD). The observation of NDBD would constitute a landmark discovery in particle physics, setting the foundations for developing a long-sought theory of fermion masses and explaining why our universe contains more matter than antimatter. The discovery of NDBD would trigger a paradigm shift in the Standard Model of elementary particles, forcing a once-in-a-century scientific revolution in particle and nuclear physics. LEGEND builds on the technological breakthroughs achieved by the AGATA, GERDA and Majorana Demonstrator experiments, which led to a design based on an array of high-purity germanium (HPGe) detectors, isotopically enriched in ^{76}Ge, operated in a liquid-argon scintillation-light detector. The LEGEND-1000 project, which is the top-ranked project in the latest US Department of Energy's "Portfolio Review", will guarantee the discovery of NDBD mediated by inverted-ordered neutrinos and, at the same time, offer excellent discovery prospects under several theory scenarios.

The LEGEND-1000 UK project is proposed to start in 2025, and its duration (5 years) is aligned with the international schedule for LEGEND-1000 construction. In the current schedule, initial procurement of the ^{76}Ge isotope and high-purity germanium detectors starts in 2025/26, with the deployment of the first detectors in 2028 and physics data-taking beginning in 2029. The construction project completion is expected in 2031. Physics exploitation funds will be requested via Particle Physics consolidated grants from 2027/28.

E1-M2 Mössbauer setup

One of the major enigmas in nature is the dominance of matter over antimatter. In terms of discrete symmetries this asymmetry is linked to the violation of combined charge conjugation (C), and parity (P), which implies time-reversal (T) violation also. Promising is the fact that nuclei with octupole correlations, so-called pear-shaped nuclei, in particular systems with an odd proton or neutron number, are perfect systems to search for such CP-violating physics in the nuclear force. Indeed, atoms and molecules containing pear-shaped nuclei are predicted to have drastically enhanced CP-violating electro-magnetic moments, e.g., electric dipole or magnetic quadrupole, and are subject to multiple experimental approaches to find such physics beyond the standard model. The E1-M2 Mössbauer setup uses a complementary approach in searching for such a nuclear CP-violating moment in the odd-mass pear-shaped nucleus ^{227}Ac. The experimental approach of resonant self-absorption is extremely sensitive. For example, in the Repka-Pound experiment this technique succeeded in measuring the gravitational redshift of photons in a tower of only 22.5m height. We estimate that we could measure an interaction energy of the CP-violating odd-moment and electromagnetic field moment created by the lattice of only 10 neV. Furthermore, the technique allows via the modification of crystal lattices to be sensitive to both the E1 and the M2 moment.

At present the tabletop-sized setup is in a rudimentary form implemented by a UWS/NPL/York/ETH Zurich collaboration at NPL Teddington and a first proof-of-principle measurement is envisaged in 2025. However, Mössbauer spectroscopy demands that the emitter and absorber nucleus are embedded in a lattice and the extremely rare and expensive ^{231}Pa emitter and ^{227}Ac absorber material is currently only available in liquid solution. Hence, the next steps must be the implementation of the availability of funding for two low-temperature dewars to freeze the two samples to the solid phase. Indeed, even when only an upper limit for nuclear E1 and M2 moments could be established, a successful Mössbauer measurement of ^{227}Ac will provide radiochemistry of these actinide elements with fantastic new opportunities.

Emerging opportunities in Nuclear Theory

Machine learning (ML) is entering a new era and will play an important role not only in nuclear physics but also in other fields of physics research. ML models have a wide range of applications, ranging from nuclear data to theory. Extensive studies are needed to gain expertise and lead future work in this field, increasing the UK's impact in future technologies.

The Nuclear equation of state (EoS) describes the correlation between energy per nucleon (E/A), temperature (T), pressure (P), and nuclear matter density. However, the behaviour of the EoS in the high-density region is uncertain and cannot be directly explored through experiments. Nuclear Energy Density Functionals (NEDFs) serve as one of the microscopic models that can connect the EoS with ground-state and excited-state properties of finite nuclei. They also explain specific observed properties of compact objects such as neutron stars. In the near future, it is expected that more data will emerge from the observations of neutron stars and gravitational waves, which would eventually be helpful to study with NEDFs to see their impact on the EoS in the high-density regime.

FAIR-RING

Storage rings for radioactive ions are unique to GSI/FAIR, and they are central to its science programme. At present both the high-energy Experimental Storage Ring (ESR), and the world-unique low-energy CRYRING are operational, and are expected to continue delivering scientific results for the next decade. In particular, the UK-funded CRYRING Array for Reaction MEasurements (CARME) is the only array at CRYRING for nuclear reactions studies of astrophysical interest. The UK also maintains a strong presence in the science programme at the ESR with its expertise in silicon strip detectors, which are being used for increasingly more sophisticated scientific investigations of nuclear properties. It is envisaged that during the next decade a new storage ring will be built, taking beams directly from the new SIS100 - SuperFRS accelerator – fragment separator complex. This will open new opportunities based on the increased beam intensities, transmission, and ring geometry. The UK will be in an ideal position to use its expertise and exploit it for studies including lifetime measurements of ground-states and isomeric states in the most exotic species, nuclear reactions of highly-charged ions etc.

Timeline of proposals not included in the prioritisation process

In the table below, “FP” represents Funded Project, “CC” represents Current Commitment, and “NCC” represents No Current Commitment.

Project	2024	2025	2026	2027	2028	2029	2030	2031
γRIBF-UK	FP	FP	FP	FP	NCC	NCC	NCC	NCC
FAUST	FP	FP	FP	FP	FP	NCC	NCC	NCC
R3B-TRT	FP	FP	FP	FP	NCC	NCC	NCC	NCC
EIC R&D	FP	NCC	NCC	NCC	NCC	NCC	NCC	NCC
EIC	NCC	FP	FP	FP	FP	FP	FP	FP
AGATA	FP	FP	CC	CC	CC	CC	CC	CC

6. New technologies

STFC nuclear physics research takes place in a wider research environment in which innovation from inside nuclear physics drives advances outside it, and vice versa. The nuclear physics community performs research in areas other than fundamental nuclear physics within the academic sphere, also working with industrial partners to exploit UKRI-funded research. Partners outside of academia support UK nuclear physics research via collaborative work including funding for staff and projects within academia. This section highlights some of these crosscutting areas, with a view to the future outlook.

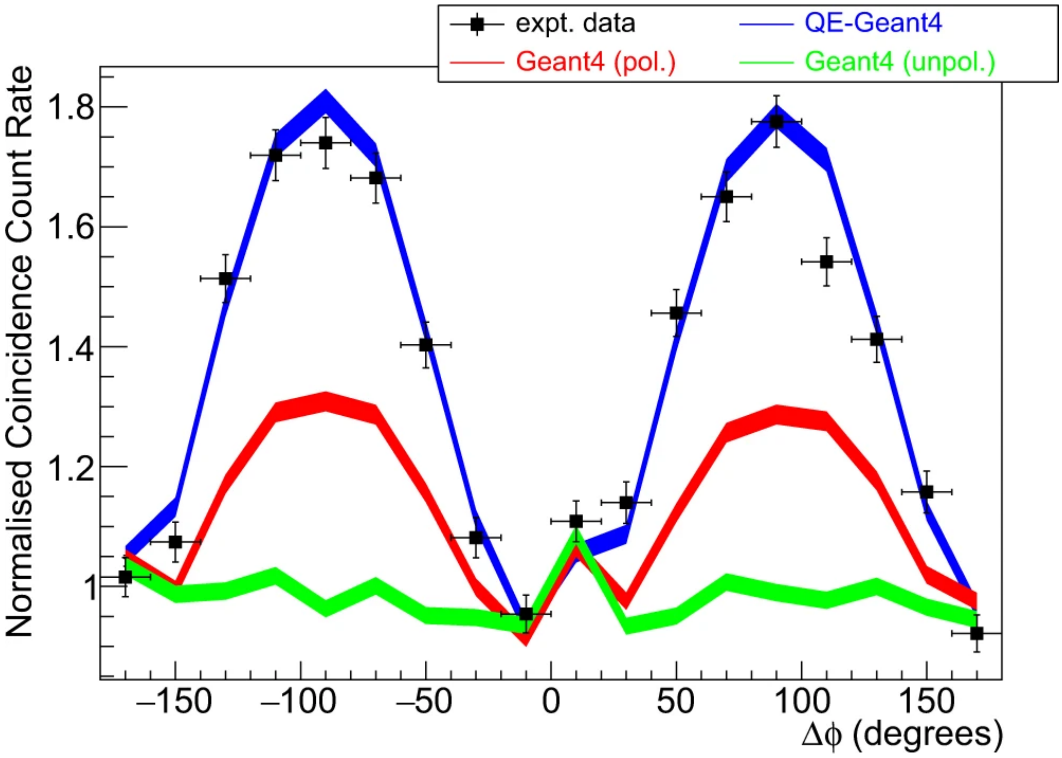

Figure 17: Black data points show the experimentally determined (normalised) coincidence count rate for double Compton scattering as a function of the azimuthal difference in scatter angles (Δϕ), obtained using the Cadmium Zinc Telluride (CZT) detector apparatus. The prediction from the quantum-entangled simulation is shown as the blue line. Non-entangled predictions for orthogonally polarised γ pairs are shown as the red line. Reproduced with permission from D. P. Watts et al., Nature Communications **12**, 2646 (2021).

The strong tradition and expertise of the UK community in detector instrumentation and data analysis crosses over into areas outside nuclear physics. For example, hadron physics analysis and instrumentation techniques have been demonstrated to reduce unwanted backgrounds in the field of positron emission tomography for medical imaging through the use of quantum entanglement in the MeV regime. Fundamental hadron spin structure research has also created significant impact through its application to address various industrial challenges. This comprises pioneering contributions to the field of cosmic ray muography, whereby scintillation-based muon detectors and likelihood-based 3D imaging techniques are used to provide powerful passive inspection of UK legacy nuclear waste containers and ageing infrastructure. Research into compact radiation detectors is positively impacting the decommissioning of nuclear facilities by providing in situ radiological characterisation in regions that have not previously been accessible. For example, through award-winning spinouts Lynkeos Technology (muography) and AevaSpec (compact radiation detectors), core research is helping to improve the safety of storage of UK nuclear waste, expedite the safe decommissioning of legacy facilities and underpinning the lifetime extension and accessibility of our critical transport bridges.

Needs of the AMBER project include development of a high pressure time-projection chamber (TPC), and vertex sensors. These developments have synergy and will benefit from on-going developments at JLab and the EIC, and other TPC activities in the UK nuclear physics community. New readout technologies are needed broadly for TPCs in nuclear physics, with current ones now becoming obsolete and unsupported. AMBER also shares technology such as particle identification and beam telescopes with the NA62 and NA64 experiments in the CERN SPS-fed North Area, fostering collaboration with particle physics communities. The UK nuclear community also collaborates with the particle physics DRD1 community to investigate replacements for harmful greenhouse gases in detectors, and in the ECFA DRD4 initiative for future Particle Identification Detectors (PID) and use of ultra-fast photon detectors which further link to areas including medical imaging and quantum optics.

Underpinning technologies for detection systems include computing and data storage and processing. Future generations of nuclear physics experiments include significant extensions need of these technologies, from exascale data storage, high data flows and complexity, and heterogeneous computing platforms (CPU, GPU, FPGA, ARM etc.). The UK infrastructure that will address such requirements is in the early stages of development, and STFC are actively surveying computing needs across users, including the nuclear community. Also underpinning detector technology is artificial intelligence (AI) and machine learning (ML), used to help process very large scale data, enable enhanced tracking algorithms and identify signals, among other uses. Such techniques are becoming increasingly widely used across the community and are certain to play a major role in nuclear physics generally, as they are across disciplines. Support of such technologies needs to be supplemented by career development and training activities for staff and students working in these areas and so consideration of this is needed in doctoral training.

Computing technologies also underpin much theoretical work in nuclear physics. A number of Lattice QCD groups in the UK require high performance computing (HPC) access to calculate and simulate low energy QCD phenomena, with recent highlights including the first calculation of a light exotic hybrid meson, with the results of expected decay modes guiding experimental endeavour. Lattice QCD work also crosses over between nuclear and particle physics depending on the quark content, and theoretical advances are readily shared between fields. The Lattice QCD community alongside those working on nuclear structure and reactions make use of HPC facilities, particularly the STFC DiRAC set of resources. Nuclear highlights include recent work pushing the limits of ab initio nuclear theory to heavier systems, and the availability of the DiRAC machines and support infrastructure is a key component in the development of the Sky3D time-dependent nuclear simulation code. Future developments in HPC technology will favour use of GPU for problems where CPUs have been preferred in the past. Work to convert codes will be needed, and support for this is vital for operation on the next generation of HPC facilities.

Quantum technologies in various guises have emerged across a range of scientific areas as important underpinning technologies as well as a vital research field in its own right. A UKRI theme of Quantum Technologies for Fundamental Physics began with seven projects in 2020 including the use and development of new detector technologies, which could become important for nuclear physics in the future, while a series of further funded projects in 2022 included Quantum Computing for Nuclear Physics and MeVQE: A World-Leading Centre for MeV-scale Entanglement Physics. Together these projects bring quantum technologies to bear in different ways to gain deeper understanding of nuclear physics; the first in the form of using quantum computers to simulate the many-body quantum mechanics at play in nuclear physics and the second to bring observed entanglement in nuclear decay products to practical application. Significant further work in these and other areas linking nuclear physics to quantum technologies is possible and destined to be a fruitful line of future work internationally, with the UK community already involved.

Key national allied research establishments which affect the nuclear physics community through cross-fertilisation of ideas, collaboration and personnel include AWE, NPL, UKAEA, and the nuclear power and decommissioning industry. These institutions benefit on the one hand from the UK University-based nuclear physics community, whilst also contributing to their support. Examples here include a supply of trained graduates to the nuclear industry and the support by industry of fellowships, studentships and projects. Such fruitful collaborations will be enhanced in the future through e.g. the development of VENOM, a new neutron facility for nuclear research at AWE.

7. Community

7.1 Nuclear Physics Advisory Panel

The purpose of the Nuclear Physics Advisory Panel is to provide a link between Science Board (PPAN) and the nuclear physics community, and represent the needs of the community to the Science and Technology Facilities Council (STFC).

The advisory panel is tasked to:

- maintain an overview of activities within the area
- develop and maintain a science vision and long term strategy or roadmap by assessing the merit of current and future science opportunities
- develop and maintain a technology roadmap for its area of research
- consult and interact with the community to ensure its views are canvassed and there is an appropriate and effective route for communication with STFC on strategic programmatic issues
- provide advice to Science Board on specific questions as requested
- liaise with other advisory panels when appropriate
- include in its remit technology development, theory, high performance computing and data curation issues within its area.

The scope of the science covered by the panel includes nuclear structure, nuclear reactions, nuclear astrophysics, the nature of the quark-gluon plasma, and the structure of hadrons.

Members

- Jacek Dobaczewski (Chair), University of York
- Gavin Lotay, University of Surrey
- Rachel Montgomery, University of Glasgow
- Philippos Papadakis, STFC Daresbury
- David Sharp, The University of Manchester
- Paul Stevenson, University of Surrey

7.2 Cross-community support

The UK Nuclear Physics community is pursuing a wide range of projects, both large and small. The cross-community (CC) team's role is to ensure all groups have access to state-of-the-art expertise in all stages of a project (planning, design, construction, implementation, and maintenance). By providing this expertise and continuity in large projects as well as during the delivery of projects not large enough to justify hiring specialists for short periods, the CC team contributes greatly to the UK community's reputation at international experimental facilities. The team is thus vital for the subject to sustain itself and to maintain the viability and credibility of the UK groups for the future.

This is achieved by the UK having a group of leading scientists and engineers who have many years of experience in 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 CC 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 substantiate ideas' feasibility 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 Nuclear Physics Grants Panel (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.

To maintain this strength of the community, it is essential to anticipate the technical and engineering skills the community will need in the future, as well as the resources necessary to manage and maintain the world-class standard of the laboratories and develop suitable technologies or evaluate the newest ones available in the market.

A well-balanced succession, training and recruitment plan taking into account the evolving requirements of the field in the following areas is vital.

With higher intensity beams emerging on the horizon at overseas facilities, the issue of event pile-up will need to be addressed. For this, expertise in fast hardware/firmware electronics and software engineering will warrant the development of high counting rate instrumentation. The development of a generic data acquisition (DAQ) system based on newer (for the nuclear physics community) platform standards (e.g., μTCA) is also foreseen. Such platforms have backplanes that enable fast serial data transfer (Ethernet, PCIe, etc.) and support synchronisation protocols (e.g. WhiteRabbit) between DAQ cards. They are also modular (using RTM or FMC cards), so they can be customised to match the mechanical and electrical connectivity of different types of detectors. It is therefore critical to maintain skills in software engineering. Mechanical and design engineering skills will remain indispensable to solve the many challenges that multi-array experimental setups present. While becoming a rare skill worldwide, target making will remain vital to the community exploiting stable and radioactive ion beam facilities on fixed targets. Finally, ML, AI and quantum technologies (QT) are becoming increasingly important in the field, with the prospect of improving existing technologies and facilitating a better understanding or new discoveries of physics phenomena. ML, AI and QT specific expertise made accessible to the community through the cross-community pool will be proposed to lower the entry barriers for UK researchers seeking to exploit these emerging technologies in their research. The UK community considers this extension of the available skills as a priority.

The UK nuclear physics CC team will aim at maintaining essential skills and incorporating new ones within the cross-community team. The role of this team will also expand to the training of the future generation of scientists, through additional activities proposed in the NP graduate school programme.

Another asset of the UK CC team is the additional technical, engineering and project management 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, engineering and project management 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.

7.3 Institutions and workforce as of 5 July 2024

The UK Nuclear Physics Community pursues its scientific activities within several institutions and universities:

Institution	**Academics**	**Fellows**	**PDRAs**	**Students**	**Technicians**
University of Birmingham	11	0	6	16	2
University of Brighton	1	0	0	1	0
Brunel University	1	0	0	0	0
University of Derby	1	0	0	1	0
STFC Daresbury Laboratory	3	0	0	0	7
University of Edinburgh	7	0	3	8	1
University of Glasgow	6	1	9	10	2
University of Liverpool	12	0	7	19	6
The University of Manchester	7	4	6	15	3
Sheffield Hallam University	1	0	0	4	0
University of Surrey	9	2	7	23	0
University of the West of Scotland	6	1	1	6	1
University of York	10	1	12	25	2
Total	**75**	**9**	**51**	**128**	**24**

7.4 Research culture

To achieve its maximum potential, a research community must train, develop and support its members, foster openness and inclusivity, encourage collaboration, maintain ethical standards, secure adequate resources, and continuously lead in research and innovation with a clear vision. These attributes define what we refer to as research culture. According to the Royal Society, “Research culture encompasses the behaviours, values, expectations, attitudes and norms of our research communities. It influences researchers’ career paths and determines the way that research is conducted and communicated.” Our community ensures a vibrant, healthy research culture by meeting these essential requirements, as detailed below.

Equality, diversity and inclusion (EDI)

EDI is integral to the operations of the UK Nuclear Physics community. Research has consistently shown that physics is among the least diverse disciplines. In alignment with the UKRI EDI Strategy and the STFC EDI Action Plan, our community actively promotes EDI and strives to enhance and support diversity within our field. This commitment is evident in our robust public engagement and outreach programmes, which focus on underrepresented communities to increase their exposure to physics, thereby attracting a more diverse student body. Additionally, our workshops and conferences adhere to the Institute of Physics guidance on conducting inclusive meetings, further demonstrating our dedication to fostering an inclusive environment. Members of our community are EDI champions within their institutes and are in an ideal position to influence EDI policy within the wider UK research community.

Outreach - Public engagement

The Community’s vision for outreach and public engagement is to leverage cutting-edge STFC nuclear physics research from across the UK to inspire and encourage young people to study and pursue careers in physics and related fields, with a particular emphasis on increasing the proportion from underrepresented groups. Given the growing demand for a technically skilled workforce, developing the STEM (science, technology, engineering and maths) pipeline is crucial.

Our community has been highly active in outreach and public engagement. Members lead and participate in established programmes, such as the Physics Olympics at the University of Liverpool and Binding Blocks led by the University of York. They organise “teach-the-teachers activities”, deliver nuclear physics masterclasses, contribute to national laboratories’ and universities’ Open Days, facilitate school visits, and serve on STFC advisory panels, such as the Advisory Panel for Public Engagement and the Public Engagement for Early-Career Researcher Forum.

The UK Binding Blocks programme exemplifies the spirit of our public engagement programme. It was established in 2015 to engage school students and members of the public. Across the UK, the STFC Nuclear Physics community aims to build upon the existing Binding Blocks programme to create a world-leading nuclear physics programme that empowers teachers, schools, young people, and the nuclear physics research community. Binding Blocks focuses on three main areas:

- Working with young people directly through online nuclear physics masterclasses for pre-16 and post-16 students.
- Empowering teachers and schools through training, a loan kit programme, teaching materials, and tailored support.
- Embedding a collaborative culture of Nuclear Physics Outreach on a national scale.

Environment

The environmental impact of all human activities is recognised by the worldwide scientific community as a principal driver of catastrophic climate change. It is therefore the responsibility of all to operate in an environmentally-conscious way. In terms of facilities, this means understanding the cost-benefit of resource use and moving continuously towards the most efficient methods and those that have the lowest carbon budget. With the move to having more meetings take place remotely, the avoidance of unnecessary air travel is a future the community must embrace. As well as generally reducing environmental impact of activities where possible, the nuclear physics community has the possibility to contribute strongly to technological means of future energy needs and other means of harm reduction in climate terms. While much blue skies research ostensibly targets different goals, spin-off technologies with the prospect of a positive climate impact should be explored with high priority.

Open Research

Open research practices are central to our community. These practices ensure research outcomes are transparent, open, verifiable and reproducible. We specifically encourage the publication of research outputs in open access journals, the accessibility of research data, and the sharing of research methodology and tools. Our community adheres to the FAIR principles (Findable, Accessible, Interoperable and Reusable) in all our practices. Additionally, we follow data sharing practices defined by the laboratories where we conduct our research and utilise their repositories for data sharing whenever possible.

Doctoral training

Our doctoral training programme is multi-facetted, comprising both institution-based and community-wide initiatives. It includes courses and lectures delivered by resident academics and visiting experts, as well as hands-on workshops and training schools.

Nuclear Physics Graduate School

The Nuclear Physics Graduate School is a community-led initiative that has been operated for around 10 years. The impetus for the initial development of the School was an IOP review of Nuclear Physics in the UK, which recommended a community-wide collaboration on PhD level education in the UK. As such, a portfolio of postgraduate courses has been developed, with different institutions making their locally offered courses available to the entire UK community. Different modes of delivery are used with some in-person, residential courses and some distance learning, online, or hybrid. In total, around 10 courses have been offered in the Graduate School including Nuclear Structure and Nuclear Instrumentation from the University of Liverpool, Nuclear Astrophysics from the University of Edinburgh, Angular Momentum and Gamma Decay from the University of Manchester, and Nuclear Theory from the University of Surrey. A popular course in the Graduate School is Hands-on Experimentation at the Birmingham Cyclotron, which offers students invaluable training and experience of setting up an experiment. Presently, the Graduate School is being refreshed to include contemporary skills such as AI and data science, and to exploit new modes of online delivery. The Graduate School is supported by all groups in the UK Nuclear Physics Community and is now recognized as an important part in the training and development of PhD students, alongside the established biennial Nuclear Physics Summer School.

Summer school

The STFC UK Nuclear Physics Summer School is a biennial event that brings together all UK Nuclear Physics PhD students in their 1st or 2nd year of study and is also open to international and industry participation. The aim of this residential school is to provide supplemental training to UK nuclear physics postgraduate researchers, and it is a vital part of their PhD programme. The school is structured with daily lectures on a broad range of nuclear and hadronic physics topics, both experimental and theoretical, and applied nuclear physics given by national and international experts in the field. These are supplemented by small-group teaching in tutorials and project skills based sessions. Additionally, there are sessions on careers, outreach and EDI built into the school. All students attending the school also have an opportunity to present to their peers. As well as the training provided the school plays an important role in community building both amongst students but also the early-career researchers who participate as tutors at the school.

SUPA Graduate School

The Scottish Universities Physics Alliance (SUPA) is the pioneering research pool that has been operating in Scotland for almost 20 years. SUPA is a collaboration between the eight institutions in Scotland which have teaching and research in physics (Aberdeen, Dundee, Edinburgh, Glasgow, Heriot Watt, St Andrews, Strathclyde, and UWS) with initial funding from the Scottish Funding Council. Since its inception, SUPA has included a Graduate School, offering the same programme of graduate-level courses to all physics PhD students in Scotland, irrespective of their home institution. In Nuclear Physics, there have been courses offered in Quarks and Hadron Spectroscopy (from Glasgow), Nuclear Instrumentation (from Edinburgh), and Data Analysis (from UWS). In order to broaden their knowledge, students can take courses from other areas of physics, as well as skills-based courses, which include machine learning, Python, Root, and Geant4. The SUPA Graduate School also includes a Scotland-wide induction event, in October each year, as well as an Annual Gathering, normally in May, and a residential two-day SUPA Graduate Careers Event; these events help to build the community of PhD students in Scotland both within the theme (Nuclear Physics) and in other areas of physics. The SUPA Graduate School is now a well-established part of the training and development of Nuclear

Physics PhD students in the Nuclear Physics Groups in Edinburgh, Glasgow, and UWS.

Early-career research culture

The nuclear physics community has historically had a vibrant early-career research culture, which suffered significantly through the COVID-19 pandemic. In particular, the lack of face-to-face meetings made the development of a national sense of community challenging, though the community continued early-career researcher (ECR) engagement through online seminars, etc. Since the pandemic, members of the community have made an effort to rekindle a national ECR culture. An annual early-career research forum event has been created, providing an opportunity for ECRs to meet, collaborate and undertake career-development activities. ECR attendance at the national IOP nuclear physics conference has been strong, providing students and PDRAs with an excellent opportunity to foster a sense of community, combined with the presentation opportunities which are vital for their career development. Finally, standalone early career events have been held, such as a satellite workshop attached to the 2024 NSTAR conference, held at the University of York. The net effect of these events is an improved ECR culture and a more cohesive ECR community.

Career Development

The career development of our students and PDRAs is a core value within our community, reflected in the comprehensive training and development opportunities we offer. Beyond the previously mentioned training and development activities, our community actively facilitates engagement with industry and exploration of non-academic career paths. These initiatives include PhD positions co-funded with industry, placements with industry partners, and the participation of leading nuclear industry experts in our workshops and conferences. Furthermore, we emphasise the cultivation of essential transferable skills such as public speaking, project management, leadership, and academic writing. These skills not only enhance employability within academia but also make our graduates and early career researchers highly competitive candidates in the broader job market.

Studentships

Funding for studentships through the STFC doctoral training partnerships is essential for sustaining and enhancing the impact of the nuclear physics community, both within academia and across various industries. Our students receive comprehensive training and development, acquiring a broad range of both discipline-specific and transferable skills. As a result, they not only contribute to academic advancements but also become highly skilled researchers who can apply their nuclear expertise to sectors such as nuclear energy, medicine, and security. Increasing the number of studentships would significantly benefit the UK nuclear physics community and bolster the country's leadership in these critical sectors. The training of students also contributes to the high-quality and well-trained nuclear work force of the UK with graduates spreading out into different fields further supporting and strengthening the UK economy.

Fellowships

Streams of fellowship funding exploited by the nuclear physics community include STFC Rutherford Fellowships, Royal Society Fellowships, UKRI Future Leader Fellowships, as well as University-funded fellowship schemes. The existence of these schemes and the willingness of the community to support the applications of ECRs to apply for them has been a continuing success story and has helped keep the field vibrant. The continuing existence and financial support of these fellowships is a high priority to encourage the best scientists to join the field. Fellowships have the scope to make a large difference in numbers to the UK nuclear theory community, and is recommended that the community makes use of existing fellowship opportunities to seed theory at more centres.

Consolidated Grants

Funding provided through the consolidated grants is essential to our community for exploiting previous investments and continuing our research programme. Preservation and enhancement of the consolidated grant line is therefore an overwhelming priority for our community.

New streams of funding

Our community would like to recommend to STFC the creation of a regular responsive-mode funding stream outside the projects line and consolidated grant mechanisms. Such a funding stream would allow the community to explore technical developments for deployment within the experimental programmes or capacity building proposals for nuclear theory, whilst also enabling the community to be more agile to emerging opportunities. This funding mechanism could be based on the recent successful Developing STFC Nuclear Physics Priorities scheme, which funded both theoretical and experimental developments. This type of funding would be more important in a situation where the consolidated grant moves to a 4-year funding cycle.

8. 10-year plan

8.1 Preamble

This Roadmap presents an ambitious and visionary 10-year plan for research in fundamental and applied nuclear physics. It attempts to strike a balance between larger-budget and new-initiative proposals that have the potential for game-changing developments in nuclear physics, and targeted and focused proposals within the core STFC PPAN programme that secure excellent physics and guarantee harmonious continuation and exploitation of programmes established so far.

The community overwhelmingly supported the plan of separating the two types of initiatives, as the targeted and focused proposals constitute the backbone of the current research programme that should be supported as a priority into the future, while the larger-scale proposals map out a strong ambition for the community looking to address the future challenges of the field.

The Roadmap presents lists of proposals prioritised separately in three subject areas:

- Nuclear structure and astrophysics proposals, which spearhead research on key scientific questions on the mechanisms leading to nuclear binding and how they influence properties of celestial bodies and the universe.
- Hadron physics proposals, which link to particle and astroparticle physics, and aim to elucidate the properties of fundamental interactions in nature in terms of the quark and gluon constituents of matter.
- General interest proposals, which aim to bring benefit not only to the nuclear physics community but often have far-reaching collaborative aspects reaching out to UKRI, industry, defence, or society at large, and for which various patterns of co-funding may and should be exploited.

It was accepted that the three subject areas are very different in scope and character. Their relative prioritisation would involve too many aspects lying outside nuclear physics to lead to sensible conclusions.

Following the principles laid down above, the Roadmap presents the nuclear physics 10-year plan in two distinct groups, “A” and “B”. “A” corresponds to proposals developing further the core STFC PPAN programme. “B” corresponds to the aspirational and new initiatives. For each group, the proposals are prioritised within the three subject areas:

- Nuclear structure and astrophysics
- Hadron physics
- General interest.

In addition, the prioritised lists of proposals are split into three zones that represent their recommended overall relative importance:

- Top-priority
- High-priority
- Medium-priority.

8.2 The list of all prioritised proposals

A	**Proposals within the core STFC PPAN programme remit**			**Costs (£M)**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
	A.Structure	**Prioritised nuclear structure and astrophysics proposals**												
		A.Structure.1	Top priority - Low-energy physics at the limits of stability	4.0	▓	▓	▓	▓	░					
		A.Structure.2	Top priority - TRISTAN@ISOLDE	6.0		▓	▓	▓	▓	░				
		A.Structure.3	High priority - Total Absorption Spectrometer	5.5		▓	▓	▓	▓					
		A.Structure.4	High priority - Studies of heavy elements	5.5	▓	▓	▓	▓	░					
		A.Structure.5	High priority - Ab initio nuclear theory	1.0	▓	▓	▓	▓	▓	░	░			
		A.Structure.6	High priority - Nuclear Structure and Dynamics	1.0	▓	▓	▓	▓	▓	░	░			
		A.Structure.7	High priority - FAIR Low Energy	5.0			▓	▓	▓	▓	░			
		A.Structure.8	Medium priority - FRIB Upgrade	6.0					▓	▓	▓	▓		
		A.Structure.9	Medium priority - Proton-rich nuclei at the limits	2.0	▓	▓	▓	░	░					
	A.Hadron	**Prioritised hadron physics proposals**												
		A.Hadron.1	Top priority - JLAB Future	5.0	░	░	▓	▓	▓	▓	▓	▓	▓	░
		A.Hadron.2	High priority - Hadron Physics at AMBER	0.2					▓	▓	▓	▓	▓	░
		A.Hadron.3	Medium priority - ELSA@Bonn	0.2		▓	▓	▓	░					
	A.General	**Prioritised general community-interest proposals**												
		A.General.1	High priority - Photon spallation source	0.7			▓	▓	░					
		A.General.2	Medium priority - ^{160}Gd double β decay	7.0	░	▓	▓	▓	▓	▓	░			
		A.General.3	Medium priority - UK centre for quantum entanglement	2.7			▓	▓	▓	▓	▓			
B	**Aspirational proposals and new-initiative**			**Costs (£M)**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
	B.Structure	**Prioritised nuclear structure and astrophysics proposals**												
		B.Structure.1	High priority - HRS@R^{3}B		R&D		▓	▓	▓	▓	▓	▓		
	B.Hadron	**Prioritised hadron physics proposals**												
		B.Hadron.1	Top priority - ALICE 3		▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
	B.General	**Prioritised general community-interest proposals**												
		B.General.1	Top priority - Nuclear Theory Centre		░	░	░	░	░	░	░	░	░	░
		B.General.2	Top priority - Nuclear Astrophysics Centre		░	░	░	░	░	░	░	░	░	░
		B.General.3	Top priority - Accelerated Beams Facility (ABRA)			▓	▓	▓	▓	▓				
		B.General.4	High priority - UK Centre for Nuclear Data		░	░	░	░	░	░	░	░	░	░
		B.General.5	High priority - UK Centre for Nuclear Applications		░	░	░	░	░	░	░	░	░	░
		B.General.6	Medium priority - Reactor neutrino flux			░	░	▓	▓	▓	▓	▓		

Timeline Preferred: ▓ Possible: ░

In this section, we present a comprehensive table of proposals considered and prioritised within the 10-year plan along with their draft 2025-2034 timelines and provisional budgets. For the aspirational proposals (part B) the budget lines are not specified as the details of their construction and stakeholders involved are very much uncertain; however, some rough estimates are available in the corresponding executive summaries that follow.

8.3 Executive summaries of the prioritised proposals

A: Structure

1: Low-energy physics at the limits of stability

A critical balance between competing nuclear structural phenomena exists at the limits of nuclear binding. The interplay here profoundly affects the composition of our universe and poses the greatest challenges to our theoretical modelling. Experimental access to such exotic species is achieved at radioactive beam facilities and in the next ten years a number of new low-energy radioactive beam facilities will be commissioned and brought into operation. At these facilities, UK researchers will have new spectroscopic access to separated and cooled ensembles of; proton-rich nuclei in the vicinity of ^{80}Zr, ^{94}Ag, ^{112}Ba, neutron-rich nuclei around ^{66}Fe and ^{106}Zr, for up to 30 new proton-rich isotopes from La to Lu, and new opportunities in actinide and transuranic elements.

The spectrometers proposed here facilitate a complete nuclear spectroscopy, encompassing the simultaneous measurements of decay characteristics, lifetimes, precision mass measurement, and, through laser spectroscopy, the model-independent extraction of nuclear spins, magnetic moments, quadrupole moments and charge radii. Determination of these key concerns in nuclear structure and nuclear astrophysics requires the development of the next generation of (laser-cooled) gas catchers and, for the highest impact, a final device mobility that facilitates “campaign deployment” at various laboratories.

Our goal is to access new, top priority (STFC science challenges C6), research avenues by utilizing the best available facility. Critical to the scope is that the developed stations and technology will be designed for deployment at MARA-LEB (JYFL), S^3 [LEB and SIRIUS] & DESIR [BESTIOL and LUMIERE] (GANIL), and FAIR with duplicated components dedicated for use at the LUMIERE facility, DESIR. All developments will be available for further, valuable, deployment elsewhere (ISOLDE or TRIUMF).

A leading role in the research effort can, for the UK, be achieved by developing and contributing to i) an advanced detection station for isotope identification and spectroscopy (β, γ, low energy photon) including fast data acquisition, ii) a laser (sympathetic) cooling RFQ / trap including solid-state laser systems (for further use in Day-1 experimental programmes), iii) the development of a fast gas cell for the delivery of the shortest lived species and iv) constructing $LaBr_3$:Ce detectors for fast-timing measurements. These activities would be scheduled to begin in 2025/26 and completed in 48 months. A total estimated cost is 3.97 M GBP with 2.49 M GBP equipment expenditure during the initial 24 months.

We will commence development of our spectrometers and gas catchers at the existing JYFL facility with the devices readied for immediate deployment at the upcoming S3 facility, GANIL and MARA-LEB facilities, JYFL. We will then, in preparation for the DESIR facility, GANIL (2027), target the components essential to deliver species from the S3 spectrometer to this new facility. Our access to Day-1 exploitation will, in all cases, be critically determined by the degree of UK involvement and contribution.

While the proposed developments are intended to be powerfully combined, individual activities, as work packages, can run independently with elements i) and ii) requiring immediate earlier effort. The packages require 24 to 36 months of development with total project PDRA effort anticipated to run for the 2 x 24 months.

Major stakeholders: Daresbury, Edinburgh, Liverpool, Manchester, UWS and York, and the JYFL, S3 and DESIR collaborations.

2: TRISTAN@ISOLDE

Key scientific drivers

ISOLDE will have several upgrades during LS3 that will increase radioactive beam yields by factors of 2-10. Parallel upgrades of the experiments at ISOLDE are needed to benefit from the additional capacity for physics. Nuclear reactions with radioactive ion beams (RIBs) can be used as selective probes of nuclear structure, provide information on important astrophysical reactions and give access to more exotic nuclei. New capabilities are needed to study many pertinent nuclear reactions. Provision of gaseous species as targets extends the available reactions with RIBs, such as the (^{3}He,d) reaction which is a **surrogate for (p,γ) capture reactions**. These reactions play a critical role in energy generation during astrophysical events, such as X-ray bursts. Additionally, the (d,p) reaction can be used as a **temperature probe for (n,p) and (n,α) reactions**, which can compete with capture reactions for example in the νp-process in core-collapse supernovae, but require light-ion coincidences to be measured between particles emitted both forwards and backwards. Reactions with gaseous species also enable more robust studies of the **evolution of nuclear structure**, where information on single-proton behaviour accessed by (α,t) and (^{3}He,d) reactions is currently out of reach. Accessing new reaction channels also opens the possibility to perform spectroscopy of very exotic nuclei, such as multi-nucleon transfer to study nuclei in the neutron-rich terra-incognita towards the **astrophysical r-process pathway**, or cluster transfer to populate excited states in odd-mass actinide nuclei, which are relevant for the search for **atomic electric-dipole moments**.

Project scope

The goal of this project is to augment the capabilities of the ISS and Miniball spectrometers to access new physics opportunities in nuclear structure and astrophysics. This will be accomplished through the addition of several novel detector advancements, providing access to new reaction channels, accessing both new physics and more exotic nuclei for study. The project will construct a second silicon array for ISS. A **dual-array mode** of operation will enable study of reactions where the residual nucleus breaks up, or multiple particles are emitted, and coincidence measurements are needed between particles that travel forwards and backwards. This new array will incorporate light-ion particle identification capabilities, giving reaction channel sensitivity. Additionally, the project will construct an active-target time-projection-chamber (TPC) at the ISS target position. This will enable the reaction vertex to be determined, provide pure targets of gaseous species for nuclear reaction measurements and access to higher luminosities - expanding studies to more exotic regions of the nuclear chart. This **hybrid-TPC** mode coupling the TPC with the ISS on-axis silicon array is a completely novel application of a TPC. The charged-particle capabilities of the Miniball spectrometer will also be upgraded by constructing an array of **novel scintillator detectors**, able to provide light-ion PID at high rates, coupled with a **high-rate tilted anode ionization chamber** to determine the residual nuclear species. The particle identification (PID) of the scintillator array will allow for the clean selection of novel reaction channels, yielding spectroscopic information on key exotic nuclei for the first time. New high-rate capabilities are vital in taking full advantage of the new intensity upgrades at ISOLDE after LS3.

Community involvement

Currently 9 UK institutions are members of the international collaborations for these two devices (Birmingham, Daresbury, Edinburgh, Liverpool, Manchester, Sheffield Hallam, Surrey, UWS and York). Work packages will be led or co-led by Liverpool, Manchester, Surrey, UWS, Birmingham and York, with cross-community support coming from STFC Daresbury.

Estimated project timescale

Submission by start of 2026 to overlap with CERN LS3. Project duration 4 years. Estimated funding requirements of approximately £5-6 million.

3: Total Absorption Spectrometer

Science Case

Understanding nuclear processes that explain the origin of the elements is consistently identified as a key challenge in nuclear physics research. In particular, elucidating the astrophysical sites and nuclear mechanisms that drive the r-process is a defining research challenge, spanning multiple disciplines. Rare isotope facilities provide a window into the extreme conditions of neutron star mergers and dying stars, pushing the boundaries of accessibility across the chart of nuclides. A next generation total absorption spectrometer, that can be moved strategically to take advantage of opportunities at multiple rare isotope laboratories, would be an ideal tool to establish UK leadership in experimental investigations of the r-process.

The systematics of β decay, nuclear level densities (NLDs), and γ-ray Strength Functions (γSFs) towards more exotic neutron-rich isotopes are essential in determining the elemental signature of possible r-process scenarios. New methods to extract these properties using total absorption spectrometry have matured in recent years, laying ground for a next-generation device that is purpose-built to carry forward these successes. Currently, most TAS devices primarily consist of NaI crystals. However, a revolution in new scintillator technology has led to higher resolution detectors without sacrificing on efficiency. A TAS device instead comprised entirely of $LaBr_3$ would represent a step-change in current capabilities by improving spectroscopic capacity without efficiency losses.

In addition to investigating neutron-rich nuclei through decay studies, a TAS device with high angular granularity for Doppler corrections can also be deployed for in-beam reaction studies. Coupled with a recoil separator, this type of next-generation TAS would possess the exceptional sensitivity needed to measure important reactions for astrophysics. For example, a TAS coupled to the EMMA spectrometer at TRIUMF, would finally realize a programme to uncover the origin of the p-nuclei, which is still a topic of intense debate. Moreover, a versatile TAS device for both reactions and decays would significantly expand the science programme for a planned superconducting recoil separator at ISOLDE.

Goals

The aim of this project is to construct a next-generation total absorption spectrometer. The device will be comprised entirely of large-volume $LaBr_3$ scintillators arranged with a geometry optimized for both in-beam reaction studies and decay spectroscopy.

A next-generation TAS would be best placed to take advantage of the highly exotic beams available at the RIKEN laboratory. However, the mobile set-up would enable other upcoming opportunities to be fully exploited. For example, this device would benefit a UK proposal for low-energy spectrometers at GANIL by providing a highly-efficient end-station with good spectroscopic capability. Reaction studies would be carried out at ISOL facilities such as TRIUMF and ISOLDE, which can produce high-quality neutron-deficient beams.

Budget Estimate

£5.5M total spread over 4 years.

Timeline:

Simulation and design work to optimise the geometry of both the full array and individual detectors will be carried out in the first year.

Testing and characterisation of individual detectors will commence by year 2.

The array will be constructed and commissioned over the remaining 2 years.

Project completion after 4 years.

4: Production, destruction and studies of heavy elements

Nuclei beyond lead are home to a wealth of emergent nuclear structure physics phenomena, as well as being of importance for nuclear energy, medicine, astrophysics and fundamental symmetries. The UK already has world-leading expertise in a number of experimental and theoretical areas related to this region, and a project to fully exploit this would be beneficial. For example, odd-A nuclei are of interest as potential laboratories for the measurement of non-zero electric dipole moments (EDMs), and require nuclear physics input to the interpretation of these results. As another example, neutron-producing (e.g. (α, n)) and -induced (e.g. (n, γ)) reactions play a key role in the creation of the isotopes themselves in the crucibles of high-temperature astrophysical collisions and explosions. The UK should maintain leadership in these areas of nuclear spectroscopy, theory and astrophysics as new laboratories and techniques become available, and researchers across the named institutes are well-placed to do so.

Increasingly, studies of nuclear structure require not only a variety of experimental probes and devices, but the use of a number of experimental facilities. We therefore envisage the creation of a portable, combined experimental device using multiple novel technologies that can simultaneously extract a variety of nuclear observables from a single measurement. We will develop an array of germanium detectors with broad-energy acceptance to give access to low-energy transitions. Novel neutron detectors will augment recent advances in (d,p) transfer induced fission (dpF) and direct measurements of neutron producing reactions such as (α, n), of relevance to the r-process. Newly-developed charged-particle detectors will provide reaction and decay path selection. The combined setup will allow for the exploitation of a number of experimental probes, including reactions and Coulomb excitation, decay and laser spectroscopy. There is a parallel need to develop theoretical methods to provide robust interpretation of the measurements performed.

The budget would encompass multiple institutions and is estimated at £5.5 million. Further to the combined setup, individual components of the project will be used individually, maximising the impact, flexibility and scientific scope of the project.

- Germanium detectors with broad energy acceptance for reactions and laser-assisted decay spectroscopy (£2 million)
- Neutron detectors for (d,p)-induced fission and (α, n) reactions relevant for the r-process, suitable for coupling with solenoidal spectrometers (£1.5 million)
- Novel detector technologies for charged-particles (heavy ions, α’s and conversion electrons) (£1 million)
- Theoretical development relevant to the actinide regions (fission, EDMs, deformation and reactions) (£1 million)

We anticipate a project starting within the next three years to coincide with the re-commencing of ISOLDE operations following LS3 and the ramping up of FRIB to full power. This will take advantage of the complementary beams available at these facilities.

The UK is already showing leadership in driving studies of actinide nuclei at the Facility for Rare Isotope Beams (FRIB) based in the US, and ISOLDE. We note that this project is supported and led by ECRs at all of the listed institutions.

Key stakeholders: Daresbury, Liverpool, Manchester, Surrey, UWS, York

5: Ab initio nuclear theory

Recent years witnessed the development of new ab initio approaches in different fields of physics, such as Atomic, Molecular, Solid State, and Nuclear Physics, aiming at explaining the world around in terms of fundamental interactions between its constituents. Ab initio approaches have been already showed their capability in predicting the physical observables correctly, with no need of phenomenological input, making them the perfect high-predictive-power calculational tools for situations where no experimental data is available. With the ongoing progress of the computational resources, such as DiRAC, as well as the computational algorithms, it is foreseeable how in the next ten years these approaches will expand their influence over all areas of Physics.

The UK theory community already started to move along this direction and efforts, led by the Surrey group, are already in place with a view to support future experimental research in major international facilities. Current efforts in Nuclear Theory are focused on developing of fast high-performance ab-initio methods for optical interactions, promising uncountable far-reaching applications both in bluesky research and industrial applications. Examples include neutron-induced nuclear data for radiation protection and nuclear waste management, high-energy nucleus-nucleus collisions in spacecrafts cause by galactic-rays, quasi-elastic neutrino scattering, pion-nucleus, antiproton-nucleus, and hyperon-nucleus interactions, with the latter opening access to the strange sector.

Other ab-initio initiatives at Surrey pave the way to computation of vital matrix elements for double β decay, α-induced reactions for nuclear astrophysics and correct observables relevant for fusion energy generation. They will also provide the needed input to describe the electron-induced reactions on unstable isotopes in future facilities, devoted to study physics beyond nuclear stability. Ab initio methods can ultimately connect ongoing developments in QCD, addressing physics on inside-nucleon level with the plethora of phenomena at a larger scale. They are ultimately related to important Physics problems, such as limits on nuclear stability, asymmetry between matter and antimatter, the existence of new physics beyond the Standard Model, that will be explored in the future.

The purpose of this project is to extend the current formalism for the ab initio calculation of nuclear optical potentials and its implementation in a computer code. The goal is to produce an open access software that can be used by the Nuclear Physics community to perform ab initio reaction calculations relevant for future experiments. The vision for this project consists of:

- 1 to 2 PDRAs based at Surrey
- Budget for travelling and maintaining the ongoing collaborations.

The recurrent staffing budget would be around £100k-200k per year. The duration of the project is of 5 years, and it will be ready to start as soon as the funding scheme is secured. The University of Surrey is the only institution involved in this project. Access to national computing resources, such as DiRAC, is of fundamental importance.

6: Nuclear structure and dynamics with density functional theory

Understanding the properties of nuclei with extreme neutron-to-proton ratios and determining the location of nuclear drip lines—maximum number of nucleons a nucleus can contain before experiencing proton or neutron emission—is one of the most significant challenges in nuclear physics. Understanding the behaviour of nuclei away from the valley of β stability and the limits of nuclear existence can help us better understand the complex nature of nuclei and modelling nucleosynthesis and stellar evolution. Therefore, development of the novel nuclear energy density functionals is essential. Implementation of the new experimental data in the optimization of the new functionals, inclusion of deformation and pairing in these procedures are important to obtain models that better describe nuclei away from the stability lines. Also, linking the ab initio approaches to the EDFs can open a new avenue in this field. These studies can also help us in our endeavours to better understand the experimental results in the formation of the new magic numbers in heavier nuclei or nuclear shape evolution and shape coexistence.

Studies on the giant resonances (GR) also carry information about key aspects of nuclear structure and dynamics. These modes also provide information about the nuclear equation of state (EOS), and precise calculations are also essential for various astrophysical phenomena. The quasiparticle random phase approximation

(QRPA), or the finite amplitude method (FAM) are known as the standard tools for studying these excitations. While these models can provide proper results in terms of the excitation energies of nuclei, they fail to describe the fine details of the strength distribution. Therefore, theoretical models need to be developed to better describe the nuclear excitations. First, inclusion of the deformation and the beyond-mean field effects, for instance, particle-vibration coupling or second random phase approximation, or finite temperature effects are essential for a proper and complete description of these excitations. Studies on this line can also help us to better understand the nuclear astrophysical processes as precise calculation of the nuclear excitations are essential.

An expected budget would involve several institutions, PhD students, and post-docs, computation, totalling around £1M over five years.

7: FAIR-UK Low-Energy

Background

The UK is associate member of the international Facility for Antiproton and Ion Research (FAIR). The UK's involvement is mainly through the NUclear STructure, Astrophysics, and Reactions (NuSTAR) collaboration. NuSTAR enjoys special status among the four pillars of FAIR, being be the first user of the new facility (the SuperFRS fragment separator will be ready first), with experiments predicted to start around the end of 2027. The UK has provided equipment such as the AIDA implantation and decay array and the FATIMA $LaBr_3$(Ce) fast-timing array for DESPEC (Decay Spectroscopy); target-recoil detector for R^3B (Reactions with Relativistic Radioactive Beams) (ongoing STFC project); CARME for CRYRING (part of APPA, which stands for Atomic, Plasma Physics and Applications); LYCCA (with Sweden) and contributions to AGATA, the γ-ray tracking array for HISPEC (High-resolution in-flight spectroscopy).

Physics case

Exploiting the uniqueness of FAIR, such as high energy fragmentation beams and already available storage rings (CRYRING and ESR), capitalising on existing UK leadership to:

- perform high energy kinematically complete measurements to address short-range correlations, quasi-free scattering, knockout, breakup etc. reactions,
- to study the properties of the most exotic (neutron and proton rich nuclei) via decay experiments, nuclear reactions (with AGATA), laser spectroscopy etc,
- perform low energy nuclear reaction measurements at existing and future storage rings for nuclear astrophysics, also addressing electron screening,
- to study the properties of superheavy elements, involving chemical, reaction, structure studies (also laser spectroscopy).

Goals

To exploit the new science opportunities offered by the multidisciplinary environment (nuclear, atomic, biology, lasers) offered by FAIR in a coordinated way. Drive the physics focusing on the future capabilities via development of experimental equipment.

Budget

Investment to update present detection systems and establish new capabilities connected to new infrastructure (e.g. laser spectroscopy in the low-energy cave, superheavy elements at the HELIAC accelerator etc. related instrumentation; all areas where the UK has leadership). Based on past investments the estimated cost is ~£5M. New storage rings under consideration will offer further emerging opportunities. A separate document requiring infrastructure funds for the R³B High Resolution Spectrometer was also submitted by Marina Petri. Note that proposed investments (PPRP or infrastructure) could lead to full UK membership at FAIR.

Key decision points

Evaluation after the commissioning of the Super Fragment Separator and SIS100 (both allow for higher radioactive ion beam intensities), and decision to furbish the low-energy branch (the building is there already, with basic infrastructure).

Proponent institutions

Institutions involved in the development of the detector setups provided by the UK: Universities of Brighton, Edinburgh, Liverpool, Manchester, Surrey, West of Scotland, York, and Daresbury Laboratories.

8: FRIB Upgrade

Physics Case

Recent observations of ancient stars indicate signatures of r-process nucleosynthesis that cannot be solely explained by neutron star merger events. As such, it is now anticipated that multiple nucleosynthetic processes are involved in the formation of heavy elements in our Galaxy. Unfortunately, advancements in this area are currently severely hindered by the unknown structure and reaction properties of medium- to heavy-mass unstable nuclei, which govern both the rate of energy release and pathway of nucleosynthesis in explosive astronomical events. Predicting the properties of these nuclei is extremely challenging and cannot be done by simply extrapolating from well-known stable systems. Specifically, as one moves away from stability, the underlying nuclear interaction causes traditional shell-structure configurations to break down, leading to the emergence of new “magic numbers” and unforeseen waiting points in astrophysical processes. Consequently, in order to address such science in the laboratory, measurements of the structure and reaction properties of nuclei must be performed at the frontiers of stability.

The recently opened FRIB facility, in the USA, is fast becoming the world’s premier fragmentation radioactive beams facility, capable of delivering a myriad of radioactive beam species to multiple experimental areas at energies from ~1 – 200 MeV/u. However, the tremendous discovery potential of FRIB can be further extended with an energy upgrade of the FRIB accelerator to 400 MeV/u for uranium and to higher energies for lighter ions. The FRIB400 energy upgrade will double the reach of FRIB along the neutron drip line into a region relevant for neutron-star crusts and to allow the study of extreme, neutron-rich nuclei such as ^{68}Ca. Furthermore, the case for the FRIB400 upgrade has been made even more timely by the dawn of multi-messenger astronomy and the detection of gravitational waves and subsequent follow-up observations of electromagnetic radiation.

Opportunity and Timeliness

The FRIB400 upgrade is explicitly mentioned in the executive summary of the 2023 US Nuclear Science Advisory Committee Long Range Plan, following Recommendation IV, which calls for investments in additional projects and new strategic opportunities that advance discovery science. A key detection instrument for the FRIB400 programme is the future High Rigidity Spectrometer (HRS). The US-DoE has already awarded \$115M of funding to develop this device and, as such, there is an ideal opportunity for UK Leadership in this area. In particular, we aim to capitalise on both our existing investment at FRIB with an upgrade of the FAUST array to make it fully compatible with HRS beamline (FAUST-II), as well as our expertise in constructing target recoil tracking devices (R^3B at FAIR) based on Monolithic Active Pixel Sensors (MAPS) through the development of a new, state-of-the-art, target recoil tracking device for FRIB400. We note that the MAP detector technology offers very attractive possibilities for further improvements in the performance of instruments used in low-energy nuclear physics, and will aid in cementing synergies with the Hadron physics community.

Budget

Based on previous developments of the FAUST and R^3B projects, we anticipate an overall FRIB upgrade cost of approximately £6 million.

Timeline

HRS construction has already been awarded \$115M and is set to be completed in 2031. The FRIB400 timeline is slightly less clear. However, the 400 MeV/u upgrade remains a priority for the FRIB facility and the planned UK developments can equally exploit existing beams on the HRS beamline prior to FRIB400. Consequently, we foresee the proposed FRIB upgrade as a high-priority in the medium-term (~2030 – 2035) with a relatively well-defined timeline, due to the already funded HRS project at FRIB.

9: Developments for accessing proton-rich nuclei at the limits of stability

Physics case and goals

Properties of proton-rich nuclei at the limits of the stability are key to answering the questions, “What governs the structure and behaviour of atomic nuclei? and What is the origin of the elements?”. In particular, electromagnetic transition rates and reaction cross sections for these nuclei test nuclear structure and reaction theories. The international facilities such as those at JYFL, HIE-ISOLDE/CERN and GANIL need essential developments in instrumentation and experimental techniques to measure such properties for exotic nuclei produced with extremely low rates.

Developments envisaged include building an Ionisation Chamber and a LaBr3 array for JYFL, a plunger setup for ISS/CERN and a Coulomb excitation chamber housing particle detectors for small-scale stable beam facilities such as those in Koln and Warsaw. These plans are aimed at obtaining complementary key data from a variety of facilities.

The ion chamber and a focal plane fast-timing LaBr3 array when coupled to the MARA and RITU separators at the JYFL stable beam facility can provide access to more exotic N~Z nuclei. These development activities will also benefit measurements planned at other facilities. For example, the LaBr3 modules can be adapted to suit radiation-energy and -timing measurements at ISS and ISRS (HIE-ISOLDE/CERN) for nuclear structure and at DRAGON, TRIUMF or at small-scale facilities such as CMAM/Madrid for nuclear astrophysics.

The MINIBALL and ISS setups will be employed to study shape coexistence and higher-order deformations in exotic nuclei via inelastic scattering reactions and lifetime measurements using plunger and charge plunger methods. These will be assisted by scattered particle detection methods in the Scattering Experiment Chamber (SEC) set up at CERN in the standalone mode and later in conjunction with ISRS. Furthermore, complementary Coulomb excitation data from stable beam measurements would enhance the reliability of the results serving as precision probes to theories.

Budget and Time Lines

The modular LaBr3 array for radiation energy and timing measurements requires an investment of £400, 000 to establish a working setup. The ion chamber for identification of recoiling nuclei at JYFL will require £100,000 to test and establish a user-friendly setup. A plunger setup inside the ISS magnet that can also be employed at ISRS or MINIBALL will open up entirely new and unprecedented measurements of lifetimes and transition probabilities that are most important to test both the shell and mean fields models for nuclei. The plunger device will need £250,000 for the development and tests at ISS. Development of a travelling-Coulex chamber with position-sensitive detectors for small-scale facilities requires £100,000. With the existing UK expertise and leadership, the timelines for development and test/initial experiments will fall in 3 to 5 years, which will be followed by exploitation mode to study nuclei in the regions mentioned above. One PDRA for each project and a PhD student for beam development activities at CERN would take the budget to approximately £2 million.

A: Hadron

1: JLab Future - UK leadership in next generation JLab science

The Thomas Jefferson National Accelerator Facility (JLab) is the world’s premier electromagnetic beam facility, the central international facility exploited by UK scientists in hadron physics studies for over a decade. The priorities of the UK-based JLab community for next 10 years are the continued exploitation of JLab, with low-cost investment enabling the potential for new leadership opportunities and scientific outputs. These goals are encompassed in the “JLab Future” program. The JLab facility has a firm plan for a major upgrade in beam intensity (by 3 orders of magnitude in 2027), advanced proposals for a positron beam and a proposed energy upgrade from 12 to 22 GeV (in the 2030’s). These give tremendous opportunities to understand strongly interacting matter with unparalleled precision, in new kinematic regimes and in heavier quark sectors (e.g. strange and charm). JLab Future will bridge the “physics gap” between JLAB and the EIC - the poorly understood transition region from non-perturbative to perturbative QCD. This project would underpin UK science leadership for the evolving JLab science programme and deliver crucial upgrades such that UK funded equipment can operate. The project is envisaged to contain three work packages - relating to the neutral Kaon beam facility in Hall D

(KLF2), the large acceptance spectrometer in Hall B (Hi-Lumi CLAS22) and precision electron scattering studies for hadron structure physics in Halls A/C (NucStruc22). The expected timeline for the JLab Future programme and more detailed information on each work package can be found in the longer reference documents.

KLF2 will enable the neutral Kaon beam facility at JLAB (underpinned by new Compact photon source technologies and realised with UK lead) to double the Kaon beam energy and increase the intensity by orders of magnitude. In parallel a new polarised target for KLF2 will be implemented. KLF2 will be the central experiment exploiting the Glue-X detector in Hall D. Key physics drivers include first access to many rare K^0 decay modes, unprecedented production rates for “very strange” hadrons at (e.g. Σ, Ω baryons to constrain both their structure and interactions for the first time). The programme impacts not only QCD - but also astrophysics due to the key role strange hadrons play in neutron stars and in early universe cooling. KLF2 will also underpin UK lead in a world leading centre for production of strange nuclei (hypernuclei), with swathes of unobserved hypernuclei coming within reach.

The **CLAS22** work package would provide UK leadership in the next generation science programmes in Hall B. The UK contribution to Hall B (the forward tagger, FT, apparatus) detects scattered e- very close to the beamline and enables a whole programme based on quasi-real photon beams. JLAB22 and/or luminosity upgrades will exceed the design specifications of the current FT, creating a major gap in the physics programme. We plan to upgrade the FT using our designs for next generation spaghetti calorimeters, a key part of the UK contribution to the EIC (UKRI IF funded), and which appear to be the only viable solution for calorimetry with the increased intensities and radiation doses.

The **NucStruc22** work package would develop UK leadership in high-rate capable data acquisition and front-end readout for a new intensity frontier at JLab in the 12GeV era (and beyond). The main physics driver is detailed structural imaging of the nucleon, light mesons and charm mesons in terms of their quark and gluon degrees of freedom, including their mass generation and spin- and momentum structures. This will be achieved by enhancing the existing facilities to run at the high luminosities required for these precision measurements. In particular triggerless electronics would cement leadership in a Tagged Deep Inelastic Scattering programme at JLab for measuring light meson structure to shed new light on the emergence of hadronic mass, and provide new opportunities for leadership in SoLID and the CLAS12 high luminosity upgrade for J/psi physics.

See the longer reference documents for the expected timeline for the JLab Future programme and more detailed information on each work package.

2: Hadron Physics at AMBER

AMBER/NA66 is a recently approved experiment in the CERN North Area, making use of the versatility of secondary and tertiary beams delivered from the SPS via the M2 beam line. Beams of muons, pions, kaons and protons are available in both charges and a momentum range between 50 GeV/c and 280 GeV/c. AMBER provides an open geometry forward spectrometer with excellent tracking and PID capabilities and a flexible detector and target arrangement which can be tailored to specific experimental needs. The current and future physics programme of AMBER has recently been endorsed and recommended in the NuPECC long range plan.

AMBER phase 1 comprises measurements of antiproton production cross sections off Hydrogen and Helium to aid dark matter searches, the first measurement of the proton form factor and radius using high energy muon beam and studies of pion structure using Drell-Yan measurements.

The Glasgow group is leading detector construction (in synergy with UK groups in R^3B) for the proton radius measurement, leading the general physics case for phase-2 and for meson spectroscopy with kaon beams in particular. This physics case will be submitted to SPSC for a timely decision early in 2025 and spans the time till past LS4. This physics case will benefit from an upgrades of the North Area as part of CERN's North Area consolidation project.

AMBER will make best use of the versatile beam and target arrangements and the capabilities of its flexible detector arrangement to study emergent phenomena. The unique beam properties make AMBER the prime Drell-Yan experiment across the world, allowing unprecedented access to the quark distribution functions in pions and kaons, disentangling valence and sea quark distributions and studying quark flavour dependent distribution functions. The same data set will allow access to the meson's gluonic content through J/Psi production. This data set will be complementary to measurements addressing some of the same physics goals using the Sullivan process e.g. at Jlab and the EIC.

Emergent phenomena will be studied through Primakoff reactions allowing the extraction of pion and kaon polarisabilities. These measurements are not only interesting and important in the study of differences between hadrons but provide deep insights in underlying theoretical models.

AMBER will be the first experiment to also study the radius of pion, kaons and protons as well as their antiparticles in the same setup, allowing for the first direct comparison of particles with their antiparticles in terms of size.

AMBER will provide prime access to the strange meson spectrum through kaon induced meson production. The planned measurements will exceed the existing measurements by AMBER's predecessor, COMPASS, both in statistics and kinematic reach. This will allow AMBER to study the strange meson spectrum in unprecedented detail and will enable AMBER to search for strange hybrid mesons.

This hadron spectroscopy programme requires an extension of the spectrometer's PID capabilities by a new RICH detector. Development will be done in parallel with EIC RICH initiatives, reducing the ask to £200k starting from 2029.

3: ELSA@Bonn Project

Physics Goals

The Crystal Barrel (CB) experiment at ELSA is dedicated to baryon spectroscopy using double polarisation experiments. The combination of frozen spin targets (hydrogen and deuterium) and tagged, linearly polarized, bremsstrahlung photons from the 3.5 GeV energy electron beam puts it in a unique position to study the spectrum of N* states. With a high sensitivity to neutral particles it has been able to compliment measurements made at CLAS at Jefferson lab (sensitive to charged final state particles), and Mainz (which has a lower beam energy of 1500 MeV). A major upgrade to CB-ELSA is planned, and includes the addition of a charged particle spectrometer; a vertex detector; a new endcap for forward calorimetry and a new electron tagger. This allows charge particle detection, pion-kaon separation and opens up a new generation of experiments with strange baryons and hyperon spectroscopy (Λ∗, Σ∗) . The Glasgow group have played a prominent role in the strangeness programme at CLAS and will participate in planning and running these experiments at CB-ELSX. Furthermore, as part of their commitment to the programme, they will build and install a pair polarimeter at CB-ELSA to improve the systematic uncertainty in beam polarization.

Cost

Participation in CB-ELSA is free. The cost of travel for shifts and meetings is about £10k per year. In recent years this has been partially funded by Horizon 2020 Trans National Access (TNA), which is likely to continue. The cost of developing and installing the polarimeter is estimated at £20k.

Timeline:

2024 - 2026: N* and Delta* measurements with polarised targets
2026 - 2027: ELSA accelerator shutdown for maintenance
2026 - 2028: Installation and commissioning of polarimeter
2026 - 2028: Installation and commissioning of detector upgrades
2027 - 2024: Beginning of Λ∗, Σ∗ programme with polarised targets and upgraded detectors

Decision Path

Excellence cluster proposal for Helmholtz Institute for Radiation and Nuclear Physics (HISKP) and Particle Physics, Bonn. Decision: May 2025.

A: General

1: Photon spallation source

Exotic nuclear isotopes are traditionally obtained from spallation of intense proton beams on (stable) target media. However, spallation using photon beams in the GeV range is a novel alternative methodology – and potentially disruptive for both pure science and medical isotope production. Photon spallation is little explored but has clear advantages over protons – the beam causes negligible heating of the target, spallation reactions occur throughout the nuclear volume (rather than near the surface) and the dominant backgrounds (pair production) are more forward focussed. The opportunities for GeV scale photon spallation are coming of age due to new Compact Photon Source (CPS) technologies – creating a new intensity frontier. These intense CPS beams underpin future UK-led experiments at Jefferson Lab (e.g. the K-long beam facility, KLF).

This project is progressing through TRL stages with York analysis of photoinduced nucleon knockout using the CLAS spectrometer in Hall B of Jefferson Lab. This is crucial to benchmark modelling of the g-induced spallation reactions viz. photoinduced many-nucleon knockout. Direct high multiplicity proton knockout from nuclei can be seeded by initial π, 2π, 3π etc. photoproduction reactions followed by (π,2N), (π,3N) etc. absorption and nucleonic final state interactions. Our many-proton knockout analysis has benchmarked the leading nuclear transport reaction model (GiBUU) for predicting spallation reactions – showing accurate predictions (within factor 1.5-2) for up to 6-proton knockout yields over g-energy ranges 0.5 to 4.5 GeV.

For realistic cells of gaseous (e.g. $Pb(C_2H_5)_4$) or thin ^{208}Pb target media and (current) CPS fluxes, the benchmarked model gives an expectation of very significant production rates of nuclei off the known nuclear chart. Nuclei 15 protons south of ^{208}Pb could be produced with rates of 100's per hour (nuclei beyond 4 protons south have never been observed). Note such nuclei are expected to have half-lives on the minute scale offering the possibility for extraction and study. There is potential to reach the long-sought r-process path below ^{208}Pb for the first time. As the exotic nuclei are produced in a direct reaction, their recoils are isotropic give exciting opportunity for direct detection in the clean environments at backward angles (backgrounds are boosted forwards). This is a new methodology – traditionally such ions are collected and subsequently extracted from a spallation cell.

We plan to request project support for targets and a prototype isotope separator (likely time of flight and Si detectors in vacuum chamber, potentially MR-TOF methods) to commission this new methodology. This will be trialled using available GeV g- beams at Mainz (10^9 γ/sec), although extrapolation to CPS intensities and baseline requirements will be quantified. An initial interdisciplinary collaboration with hadron physicists (Watts, Bashkanov, Zachariou) and nuclear spallation experts in York (Jenkins, Cubiss) and Surrey (Doherty) is in place.

Clearly, one future implementation would be with CPS at JLAB. However, with successful R&D we are interested in exploring if a world-leading UK facility (requested via UKRI IF) is feasible – bringing in the UK's leading electron accelerator expertise (e.g. ELI and EIC).

Timescale

2027/28

Estimated cost

£0.7 million

2: ^{160}Gd double β decay

Double β decay is one of the rarest nuclear phenomena. Only 35 isotopes are predicted to exhibit double β decay, i.e. the simultaneous conversion of two nucleons. Of these 35 candidate, only 11 isotopes have been experimentally confirmed to undergo double β decay (a further 3 show double electron capture). The observed half-lifes are typically on the order of 10^{20}y or more. Two modes of double β decay are discussed - the two neutrino double β decay and the neutrinoless double β decay. For the former, two electrons and two neutrinos are emitted. For the latter, only two electrons and no neutrinos are emitted. The observation of the two neutrino double β decay is of profound importance for our understanding of nuclei and nuclear structure, as the observed half lives are very sensitive to nuclear structure calculations.. The implications of observing the neutrinoless double β decay are even more profound. It would be a direct observation of the violation of lepton-number conservation. Its observation implies the Majorana nature of at least one neutrino flavour. The observation of the Majorana-like nature of neutrinos will have wide ranging consequences, e.g. in setting the absolute mass scale for the neutrino mass and important evidence for the see-saw mechanism. It would also provide an important candidate for cold dark matter in the universe.

A number of experiments worldwide are looking for this reaction, yet none for the isotope proposed here,^{160}Gd. Two limits have been set using inorganic scintillator crystals for its half-life. The advent of a novel Gadolinium rich detector material and silicon based photon counters allows significant improvements in energy resolution and background conditions over previous experiments. STFC's Boulby Underground Laboratory provides the ultra-low background conditions to successfully conduct this experiment. This proposal aims at using existing applied nuclear physics technology in a novel combination to design, construct and evaluate a prototype detector system for a first measurement of double β decay of ^{160}Gd within the first 5 years of the reporting timeframe, with an extension to an internationally leading facility in the second half of the decade, based on lessons learned during the pilot run. The proposed pilot in itself should push the current limit by at a factor 3 over 1 y running time. The total cost for a pilot installation (without manpower) is expected to be ~ £200k. The lessons learned will then inform the installation of a larger detector array.

The current best limit for neutrino less double β decay is about 10^{26}y, with predictions for ^{160}Gd varying around 10^{23}y, which is about 2 orders of magnitude above the current limit. A precise evaluation requires knowledge of the background conditions on Boulby mine in a specific setup, which is one aim of the pilot run. Assuming a 10y running period and 100 detector modules, proving or disproving the limit of 10^{23}y seems feasible. The cost of the installation will be about £7M without personnel.

3: UK centre for quantum entanglement and quantum computing

We propose a new interdisciplinary centre which will bridge the current gaps between the nuclear and particle physics communities and the UK's quantum information (QI) communities. The scientific impacts and utility of quantum entanglement (QE) and QI in nuclear and particle physics is taking early steps. Nuclear physics researchers successfully leveraged funding in this area from the interdisciplinary Quantum Technologies for Fundamental physics (QTFP) call, which has seeded new initiatives. For example, the UK has a current international lead in next-generation measurement and application of photonic QE at the MeV scale (γ photons), leading advances in the extraction of QI with modern γ detector systems, the first QE particle simulation (using the framework of Geant4) and the first calculations of (and test of) QE decoherence at the MeV scale. These advances were catalysed by the MeVQE centre at York (Watts), supported under QTFP, bringing together quantum information scientists, mathematicians and physicists to progress the field in theoretical and experimental aspects. The Surrey group (Stevenson) also received QTFP support to pioneer quantum computing (QC) in next-generation nuclear theory including QE in the nucleus. There are exciting possibilities to use QC to overcome current classical computing limits, which mean fundamental calculation of swathes of nuclei remains unreachable.

Such progress is however only the tip of the iceberg - the scientific landscape is rich and largely untouched. There is clear potential to enhance leadership and create critical mass in this new area. For example, the entanglement of g in cascade nuclear or meson decays is unexplored. Higher multipartite entanglement, e.g. 3-g QE, will come within reach and give new fundamental tests and routes to constrain CP and CPT violation. Distance-based tests and space-based experiments reaching accelerations challenging General Relativity effects in QE could be feasible. UK-led initiatives at Jefferson Lab (e.g. KLF) offer exciting opportunities for hadronic entanglement measurement (e.g. K^0 mesons). The predicted QE of the 2-g from p, h, .. meson decays remain unmeasured– but would be a first clear test of photonic entanglement in relativistically boosted frames. Opportunities exist for many new and impactful programmes at RHIC, EIC, LHC and many other facilities worldwide.

We propose a UK centre for next-generation QE and QI in nuclear and particle physics and applications. Current UK leadership in QE and quantum computing will seed a new centre with greatly expanded scope and training opportunities. The centre will comprise around 20 NP, PPE, PPT and QI academic colleagues, with the aim of catalysing UK-led QE programmes at international accelerator facilities, cutting-edge QE theory as well as underpinning applications projects. Commercial partners in medical imaging, nuclear and other industries where MeV scale QE has transformative potential will be embedded in the delivery board. The funding would support interdisciplinary PDRA effort working across the new community, PhD studentships and funding for meetings and management.

Timescale

2027/28

Estimated cost

£2.7M (5 year duration in first instance: 2 PDRA (£0.6M), 3 PhD studentships - £1.5M (including overseas fees to make one post open for international applicants), meetings and administration (£0.3M), quantum computing access (£0.1M), Consumables and infrastructure support (£0.2M).

B: Structure

1: Enhancing the R^{3}B capabilities at FAIR with a High-Resolution Spectrometer

The recent observation of gravitational waves from neutron-star mergers is one of the most exciting scientific developments of this century and signalled the birth of multi-messenger astronomy to study these celestial objects. However, there are many open questions regarding the properties of neutron stars, like their composition and size. Even though these are astronomical objects, nuclear physics plays a critical role in understanding them, much in the same way it impacts our understanding of nucleosynthesis and the formation of elements in the universe. To better understand neutron matter and neutron stars, it is vital to probe properties of very exotic nuclei.

The R^{3}B experiment at FAIR is a versatile setup with significant UK investment that enables a broad physics programme with high energy radioactive-ion beams. It consists of state-of-the-art instruments that are specifically designed for the beam energies and intensities delivered at FAIR. UK academics are core members of the R^{3}B collaboration, which has 50 participating groups worldwide, and have leading roles, e.g., the Scientific Director, and members of its management, technical and collaboration boards. In 2022, a review into the “early science” of FAIR took place and the installation of S-FRS and the associated R^{3}B setup was recommended with highest priority, confirming the importance of the R^{3}B experiment and its competitive standing worldwide.

This project aims at developing a high-resolution spectrometer for the R^{3}B setup to study relativistic-energy nuclear reactions with the intense beams from SIS100. This proposed development not only exploits the significant increase in beam intensity, but also utilizes the higher beam energies (that will be uniquely available at FAIR) to enable much cleaner particle identification of heavy-ion reaction products (free of charge-state contamination). This is a critical feature for studying the key structural properties of very-neutron rich, heavy, radioactive nuclides, offering unique constraints into our understanding of the properties of neutron stars (through detailed studies of highly proton/neutron imbalanced systems). High resolution is critical to all these studies to fully resolve different excited-state configurations populated in the reaction process and allowing high-precision measurement of the momenta of nuclei following nuclear reactions. These new capabilities enabled by the proposed investment do not exist at any other facility in the world.

This project will catalyse the UK’s position in FAIR science programme and gives a unique opportunity to take the lead in the construction of the High-Resolution Spectrometer at R^{3}B with significant investment. A strategic objective would be to elevate the membership status of the UK from present associate to full member status because of this investment. Full membership at FAIR will bring major benefits regarding science, technology, training and skills. FAIR membership will facilitate access to word-class nuclear physics, it will help to attract young talent and it will provide access to and facilitate the development of state-of-the-art nuclear technology.

This project will be divided into two phases:

i. Finalising the design of the R3B HRS, and
ii. Constructing the R^{3}B HRS following the Technical Design Report developed in Phase-I.

Stakeholders: All UK FAIR members

B: Hadron

1: ALICE 3

ALICE 3 is a major new and comprehensive detector for the LHC optimised to carry out an extensive programme to fully exploit the heavy-ion beams for the study of the properties of the quark–gluon plasma. It will replace the current ALICE detector and be operational during LHC Runs 5 and 6, from 2035.

The ALICE Collaboration proposes a novel detector with high readout rate, superb pointing resolution and excellent tracking and particle identification over a large acceptance, using advanced silicon detectors. To optimise the pointing resolution, the first tracking layer must be placed as close as possible to the interaction point in vacuum. The detection layers are constructed from wafer-scale CMOS Active Pixel Sensors thinned to ∼30 μm and bent into cylinders to minimise the material. An outer tracker with barrel and endcap layers provides a relative momentum resolution of 1-2% over a large acceptance by measuring about 10 space points. The large active area of the outer tracker requires the exploitation of commercially available, high-volume, production processes, ranging from CMOS technology for the sensors to highly automated bonding techniques for module integration. For particle identification, a time-of-flight detector and a ring-imaging Cherenkov detector cover a broad momentum range, both relying on novel silicon timing and photon sensors. R&D programmes are being set up to push current technological limits of silicon sensors for tracking, timing, and photon detection. Photon detection and lepton identification at higher momentum are provided by an electromagnetic calorimeter and a muon identifier, both of which exploit established detector technologies. A forward conversion tracker measures photons at very low transverse momentum, through their conversion into electron-positron pairs at forward rapidity.

The UK groups involved in ALICE 3 aim to use their technological expertise in CMOS MAPS to contribute to the Outer Tracker and Trigger. The Si detector is based on 11 barrel layers and 2 x 12 forward discs. It is divided into a Vertex Detector made of the first 3 layers and 2 x 3 discs, retractably mounted inside a secondary vacuum and of length 50cm, and the Outer Tracker. It will cover the “central” pseudorapidity interval of $|\eta| = 0.4$, with longitudinal and radial extensions of +-400cm and 0.5-80cm, respectively. The total area of the charged particle detector is 70m2. Each layer will be constructed from staves, each of which is made from modules.

CMOS Monolithic Active Pixel Sensors (MAPS) are considered the baseline sensor technology for the vertex detector and the outer tracker. The Tower Partners Semiconductor Co. Ltd (TPSCo) 65nm, CMOS imaging, manufacturing process is taken as reference, though other processes will be considered. We will use the experience that we have gained from using CMOS MAPS for ITS2 and ITS3 in ALICE and in the EIC SVT.

Based on our relevant experience in the recent upgrade of ALICE in its trigger and Si vertex and tracking detectors (ITS2), we estimate that the costs would be on the order of £20M. More context is also available in a longer statement on future ALICE 3 activities available at ALICE 3.

Key stakeholders: Birmingham, Derby, Edinburgh, Lancaster, Liverpool, QMUL, STFC (PPD, TD at DL and RAL).

B: General

1: Nuclear Theory Centre

Nuclear theory is essential to advancements in our understanding of the nucleus and its interactions. Equally, it is a key capability underpinning applications of nuclear science vital to UK interests. Such applications include civil nuclear energy (fission and fusion), national defence, and radioisotope production for medicine. Nuclear theory also plays an often underappreciated role in supporting fundamental physics studies and nuclear astrophysics, thereby building bridges with other PPAN areas such as particle physics, particle astrophysics, and astronomy. For example, the probability of observing neutrinoless double β decay critically depends on nuclear matrix elements that are challenging to model reliably.

The objectives in establishing a UK Centre for Nuclear Theory would be:

- To achieve **international leadership** in nuclear theory and to influence the future direction of nuclear physics worldwide.
- To provide **sovereign capability** that can be called upon for all applications of nuclear science in the UK, securing such capability into the long term.
- To provide **strong theoretical input and direction** to the experimental nuclear physics programme in the UK.
- To provide **essential theoretical underpinning** to the wider PPAN programme in fundamental physics and astrophysics.
- To provide **high quality training** in nuclear theory at both MSc and PhD level to resolve the pipeline problem in this area to wider national benefit.
- To ensure a **critical mass** of nuclear theory in the UK to give sufficient opportunity for employment and career progression for future generations of theoreticians.

Our vision is for such a centre to grow organically over the next decade reflecting the need to restore a pipeline of early career researchers in nuclear theory in the UK. Given the focus of the proposed Centre, we would expect funding to come from a diverse range of sources including UKRI, direct government funding, industry, and universities. In its steady state, the Centre might have around five research themes such as nuclear structure, nuclear reactions, hadron physics, fundamental physics and astrophysics. Initial research objectives in these sub-disciplines could be targeted around answering one of the internationally identified key questions in nuclear physics. We would expect strong cross-fertilization of ideas across these theme boundaries. To achieve critical mass, each theme would require 3 or 4 academics associated with it, with around 6 PDRAs/independent researchers and 10 PhD students. This leads to an estimate of a recurrent staffing budget of around £1.5M per research theme per year, or £7.5M/year for the Centre as a whole, with a gradual increase to reach this level over the first five years.

The Centre would likely be distributed across several sites in the UK at universities and/or national laboratories. Access to a significant compute resource on a regional/national level would be essential. Combining or co-locating a Centre for Nuclear Theory with the proposed UK Centre for Nuclear Data (q.v. below) would add significant value as nuclear theory is a crucial underpinning capability in any nuclear data activities. Such a connection would also cement the links to wider UK industry and strategic needs.

Key stakeholders: UKRI, STFC PPAN community including PP and APP, NNL, NPL, AWE

2: Nuclear Astrophysics Centre

Background

Nuclear Astrophysics is an interdisciplinary field at the intersection of nuclear physics, astrophysics, cosmology, atomic and plasma physics. As such, major advances require inputs from all these areas both at experimental, theoretical, and observational level. However, traditional UK funding mechanisms make it challenging for different communities to come together and synergically exploit much needed expertise from different domains. The creation of a **Nuclear Astrophysics Centre** aims at overcoming this challenge by advocating the need for a sustained stream of funding to foster collaboration across boundaries. The Centre builds on the demonstrated success of previous initiatives, both in the UK (e.g. BRIDGCE, NuGRID, ChETEC) and overseas (JINA, NAVI, IReNA, ChETEC-INFRA).

Vision

The recent advent of multi-messenger astronomy has opened a doorway to a new era of scientific discovery. To achieve major breakthroughs in our understanding of how the universe evolved, we must combine breath-taking astronomical observations with remarkable advances in accelerator-based nuclear physics and theoretical modelling of stars. Unifying these three communities through a UK Centre of Excellence will allow us, for the first time, to obtain complete and fully consistent answers to the mysteries surrounding the origin of the chemical elements, while also providing a clear vision for the future directions of nuclear astrophysics worldwide.

Physics case

Exploring the chemical evolution of the Universe from its early stages to the present day, through a better understanding of Big Bang Nucleosynthesis, the formation and evolution of first stars and galaxies, and the emergence of heavier and heavier elements during both quiescent and explosive stellar evolution.

Goals

To facilitate the exchange of information, interaction and collaboration across different disciplines, through a sustained funding mechanism to support a broad programme of initiatives, including:

Funding for PDRA posts, PhD studentships, and MSc scholarships in Nuclear Astrophysics, specifically for cross-community projects otherwise difficult to support through standard funding routes and co-supervised with other institutions.

Seed funding to establish, foster and consolidate **collaborations** in Nuclear Astrophysics across the UK, overseas, and with developing countries.

Visiting Programmes, open to students, ECRs, and staff both from the UK and overseas, to facilitate participation in research activities.

Training activities (e.g. on stellar simulations, reaction networks, nuclear reaction theory, R-matrix formalism, detectors, accelerators, etc.), specifically tailored to Nuclear Astrophysics students (UK and overseas).

Cross-community workshops to foster communication across experiment, theory, and observation.

Access to experimental facilities both in the UK (e.g. Birmingham cyclotron and neutron source) and overseas.

Sketch of the budget line:

£5m over the first 5 years, plus another £5m after a mid-term evaluation.

Breakdown of total costs over 5 years:

2 two-year PDRAs/y (£1.2m)
3 four-year PhD studentships*/y (£2.64m)
3 one-year MSc by Research/y (£450k); 10 visiting bursaries/y (£350k)
2 workshops/y (£100k)
1 summer school/y (£100k)
oversight committee (£50k)
programme administrator (£150k).
*includes international fees (at £20k/y) and travel allowance (£4k/y).

(See the full document for the list of proponents and supporters: Nuclear Astrophysics Centre Centre.)

3: Accelerated Beams for Research and Applications (ABRA) – A National Cyclotron Facility

Background

Beams of stable ions underpin a large number of research fields within the nuclear sciences, from understanding the origins of the elements, to measuring data pertinent to reactor safety cases and much more. The existing Birmingham MC40 Cyclotron Facility – the UK's only medium-energy research machine – supports a wealth of UK and international collaborations in many areas, but can only produce beams up to helium-4, and daily NHS-isotope production means a very limited science programme. A high energy, high current and high beam mass National Cyclotron Facility is proposed to address this deficit, powered by a K≥70 machine with ECR source for heavy-ions and high-intensity light-ion beams enabling cutting-edge research for both pure and applied themes. Utilising the existing infrastructure, and staff technical expertise of the Birmingham MC40 and HF-ADNeF neutron source, will lead to a cost-effective national research centre in the heart of the country.

Physics Case and Goals

This facility at Birmingham will enable stable-beam experiments in the areas of nuclear structure (few-body systems, shape coexistence,...), nuclear astrophysics (mainly indirect techniques but some complementary direct studies), radionuclide production (including for medical applications), fusion power, nuclear data measurements and detector development (including radiation hardness testing for space and other applications). The focus of international facilities on beam-time for radioactive ion beams (e.g. JYFL/GANIL/FRIB/RIKEN) means that there is an ever increasing shortage of stable beams for physics programmes. A domestic facility would allow UK-community needs to be met in terms of stable-beam science, e.g. feasibility studies, testing for international detector-related projects – as well as providing much needed training opportunities for students and nuclear professionals. This facility will deliver an impactful science programme and boost UK research efforts across the full spectrum of nuclear research as well as forging links between fundamental science, applications and industry. The facility will have multiple beamlines and experimental end stations to address the needs of the UK Nuclear Physics community.

Proposed beamlines:

1) Charged-particle studies
2) γ spectroscopy
3) Low-background, long-flightpath neutron spectroscopy area
4) Combined charged-particle and neutron-beams from HF-ADNeF (world exclusive)
5) National Physical Laboratory/UK Atomic Energy Agency industrial partners.

Budget and timeline

The machine installation costs are £35M and takes 4-5 yrs, with an additional ~£10M for infrastructure due to savings from using an existing building. Engagement with the wider PPAN and EPSRC communities will be sought to maximise the impact of the facility activities with the aim of submitting a full UKRI infrastructure bid in 2026.

Stakeholders: UKRI, STFC PPAN Community including PP & APP, NPL, UKAEA, AWE, NNL, Nuclear Medicine.

4: UK Centre for Nuclear Data

Nuclear data is vital to various critical UK interests from nuclear energy to national defence and is therefore arguably one of the most important applications of the knowledge and skills derived from the fundamental research programme in nuclear physics in the UK. Despite this, the UK's capacity for nuclear data studies is presently at a very low level following the decline of the wider nuclear industry over the past decades. Indeed, what presently exists comprises pockets of resource-limited expertise within industry, universities and national laboratories. In terms of visibility and funding, nuclear data has long struggled in terms of whether it falls into STFC's remit as a high-profile application of fundamental nuclear physics research, or whether it belongs in EPSRC's much wider energy remit. This has led to nuclear data-related research in the UK being marginalised. It is notable that no other major Western country involved in significant exploitation of nuclear science has anything like such a limited underpinning capacity in nuclear data.

Nuclear data needs in the UK are broad and rapidly growing. While nuclear data for the existing fleet of reactors in the UK is well established, obtaining new data starts to become critically important as the UK seeks to invest in small modular reactors (SMR), and future generation IV reactors which will operate at higher temperatures and under different fuel loading. Moreover, the nuclear data needs for successful exploitation of nuclear fusion are many and presently challenging. Wider applications of nuclear data include establishment of national and international radioactivity standards, and applications in the production and safe employment of radioisotopes in medicine. Nuclear data needs also underpin renewal of the nuclear deterrent. Other defence and security related applications include nuclear non-proliferation and nuclear forensics.

Nuclear data entails a complex pipeline. It begins by identifying specific data needs in conjunction with relevant stakeholders. This may define requirements for further experimental work e.g. to measure reaction cross sections with higher precision within certain energy ranges, entailing work at accelerator centres in the UK or abroad. Such data then needs to be analysed and put into a form where it is useful to industry and other users such as being implemented into relevant international databases. Other complex aspects include Monte Carlo simulation, reactor modelling, covariance analysis etc. Nuclear theory, especially, nuclear reaction theory is a key underpinning capacity related to nuclear data work.

A UK Centre for Nuclear Data would ideally be an academic/industrial partnership that seeks to leverage the skills and expertise deriving from UK physicists' ongoing work in fundamental nuclear physics. The Centre would showcase the value of engaging in such fundamental research for the UK economy. A Nuclear Data Centre would require new-build or repurposed office space and lab space to allow for in-house measurements, experimental preparation and limited detector R&D. Steady state staffing for a Nuclear Data Centre would typically include a Director (holding an academic chair), four further academics, and six post-doctoral researchers/independent fellows, 10 PhD students as well as an experimental officer and a technician to support the laboratory spaces. A Centre would hold recurrent funding to enable lab-based R&D as well as to support travel to national and international facilities. Internal fellowship funding could support sabbaticals by academics/PDRAs into the Centre from fundamental physics areas as well as secondments into and out of relevant industrial partners. Value would be added by co-locating or otherwise linking to proposed UK Centres in Nuclear Theory and Radioisotope Development. A recurrent annual budget of around £2M is estimated with expectation that a large component of this would be match funding from relevant industry.

Key facilities: nToF at CERN; NFS at GANIL, Birmingham Cyclotron, NPL Neutron facilities, NIF, Ill, ESS.

Key stakeholders: UKRI, STFC, EPSRC, Innovate-UK; UK Nuclear industry: NNL, EDF, Jacobs etc.; CCFE Culham, fusion startups; AWE; NPL, IAEA; Radioisotope developers e.g. Urenco.

5: UK Centre for Nuclear Applications

Of the PPAN science areas, nuclear physics stands out as being arguably the one closest to real-world applications. The areas of application are broad from homeland security to nuclear decommissioning, from borehole logging to medical imaging.

Applications stemming from nuclear physics often focus on transfer of detector technology to such real-world applications but transfer of domain-specific expertise and techniques can be equally important. Recent examples of the latter include quantum-entanglement of annihilation photons being exploited as a means to improve positron emission tomography. Many such emerging aspects of nuclear physics experimental work related to quantum technology remain to be exploited for real-world applications. Examples include exploiting the ^{229}Th isomer as a nuclear clock which could be revolutionary for technologies such as GPS.

The aim in establishing a UK Centre for Nuclear Applications would be to showcase the value of underpinning fundamental research for real world applications. The intention would be for the Centre to generate a net profit to the UK economy and industrial partners within the first 5-10 years. The Centre would also train a workforce of early career researchers of high value to industry. In particular, the Centre, with a strong industry connection would draw on and support existing applications-based research across University groups and focus on helping to bridge the gap to high TRL levels needed so that real-world applications can be realised.

An initial vision for a UK Centre for Nuclear Applications would be a physical centre combining significant laboratory space for detector development with an attractive and open design to ensure that the Centre was industry-facing and welcoming to visitors. The UK has strong expertise in various detector technologies such as gas/ionization detectors, scintillator crystals and semiconductors including germanium, silicon and CZT. Handling these various strands of technology would require more specialist facilities such as cleanrooms and gloveboxes. The laboratories would also require facilities to test equipment under industrially relevant conditions of elevated temperature and pressure. Aside from physical infrastructure, digital data acquisition systems able to handle high numbers of channels would be required. The startup costs for the Centre based on a bespoke building plan and fit out would be of order £10-20M.

Steady state staffing for a Nuclear Applications Centre would typically include a Director (holding an academic chair), four further academics, six post-doctoral researchers/independent fellows, and 10 PhD students. An in-house electronic/mechanical workshop would be essential with access to equipment such as industrial 3D printing facilities for fast prototyping. Alongside an experimental officer to oversee the laboratory spaces, the requirement would be for 3-4 technicians of various functions. Given the industry-facing nature of the Centre, it would be essential to have a business development manager and a knowledge exchange and commercialisation fellow to support the Director in growing the Centre's industrial network. Funding would also be required to support fellowships/placements of staff in and out of the Centre from both UK universities and relevant industrial partners. Staffing costs and overheads for such a Centre would be £2M-£3M per year with the expectation that there would be significant industrial buy-in and match funding.

Key Stakeholders: STFC, Innovate UK, Createc, Kromek PLC, LabLogic, Micron Semiconductor, Mirion, Rolls Royce, AMRC, NPL, NNL, Sellafield

6: Reactor neutrino flux

STFC is developing the existing Boulby underground laboratory in Boulby mine near Whitby in North Yorkshire with the specified aim to become a world class laboratory to investigate dark matter and other rare phenomena. Members of the NHP group at the University of Glasgow are already actively engaged in the development of detector technology for future neutrino measurements both for fundamental science and nuclear safe-guard applications. These involvements, together with the applied nuclear physics team working on muography provide an ideal foundation for proposing new experiments in the current and future laboratories in the Boulby mine. It should be noted that the current laboratory is active and excavations for the next phase are expected to start imminently. The proposed work hence ideally fits the NPAP horizon of up to 10 years.

The Boulby underground laboratory was chosen to host the AIT-NEO neutrino detector as an instrumentation testbed and neutrino detector monitoring the nearby Hartlepool nuclear power station, pursue supernova studies and more. The original AIT-NEO design and installation was halted due to a change in operating plans by EdF, the operator of the Hartlepool nuclear power stations, bringing them to retirement in 2028, before the detector could have been operational.

The function as an instrumentation testbed for novel neutrino detector technology with applications for fundamental research and nuclear threat reduction has been taken over but the BUTTON collaboration, installing a 30t detector system in the existing Boulby lab in 2024.

The BUTTON collaboration and its national and international partners are working closely with STFC on the design and realisation of the upgrade of the laboratory in the Boulby mine. It is envisaged that the new facility will house a neutrino detector with a 1 kiloton fiducial volume based on the technologies developed through BUTTON, including novel photon detectors and novel fill materials to be deployed underground for the first time, bringing UK scientists to the forefront of underground and low background detector technology.

On a similar timescale, i.e. by the end of the decade and throughout the 2030s, EdF is planning to replace the existing Hartlepool reactors by a fleet of Small Modular Reactors at the same or adjacent site. The combination of a new set of reactors with a nearby underground neutrino detection facility with advanced instrumentation and a fiducial volume on the kiloton scale provides the opportunity to fulfil the original AIT-NEO science programme and for the first time study the nuclear security implications of a set of modular reactors in real time. The total project costs are currently evaluated and are expected to be on the order of £20M.

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