Nuclear Physics Advisory Panel - Roadmap

The main science questions extracted from the NPAP report were (a summary of the scientific context is given later in the current document)

1. What are the Origins of the Elements?
2. What is the Nature of Nuclear Matter?
3. How do the properties of hadrons and the quark-gluon plasma emerge from fundamental interactions?

Key Science Questions

Rather than extract one of the above three questions as a representative of nuclear physics an approach which is more representative of nuclear physics would be preferential. We urge PPAN to adopt two key nuclear physics questions…..

- **What are the Origins of the Elements?**
- **What is the Nature of Nuclear and Hadronic Matter?**

We cannot construct a single question which combines the two above in a way which is satisfactory.

Roadmap

It is important to note that in the way it operates nuclear physics is more similar to astronomy than particle physics, in that rather than concentration on a few facilities, equipment is built to be used at a number of experimental facilities to answer a range of scientific questions across the spectrum of the science (e.g. ISOL-UK, AGATA etc.). A crucial element of the Science programme is the exploitation of the network of Scientific Facilities worldwide. This exploitation programme spans fragmentation, ISOL, stable and electron/photon beam facilities and should be given appropriate emphasis in a roadmap. This is recognised in the above diagram.

Roughly two thirds of the nuclear physics spend goes on science funded through the grants line, which uses a wide range of facilities dependent on the needs of the specific research programme. Over the next decade some will reach the end of their useful life, but many have significant upgrades planned or in progress which will ensure that they remain forefront facilities which the UK community will continue to exploit for specific research goals.
Projects and Future Facilities
It should be noted that this list reflects a list of future opportunities and has not been prioritised, but reflects the sequences of topics in the above diagram.

- **R3B, HISPEC, DESPEC at FAIR, GSI, Germany [2010-2015]**: Currently funded project to study nuclear structure at the extremes of neutron-richness, search for new magic numbers, new nuclear symmetries and study the formation of nuclei produced in the r-process – currently associated with reactions in supernovae.

- **Upgrades to R3B, HISPEC and DESPEC and new projects EXL, ELISe, ILIMA and LaSPEC at FAIR, GSI [2015-2020]**: Upgrades to improve physics reach of the current generation NuSTAR projects, plus future projects at FAIR, GSI, Germany: precision measurements of nuclear structure at the extremes of neutron-richness using storage rings. The EXL project requires the development of silicon detector and readout technologies which can operate in ultra-high vacuum necessary for storage ring operation.

  Technology development challenge: experiments performed in storage rings require both complex detectors and hundreds of thousand spectroscopic grade channels of electronics to be operated in ultra-high vacuum. The technology to achieve this remains to be developed.

- **AGATA [2010-2013] AGATA (upgrade) [2014-2018] at NuSTAR, SPIRAL2 and Legnaro**: AGATA will play an important role at FAIR and SPIRAL 2. It is a state-of-the-art gamma spectrometer which has tracking capability and hence the ability to localise the interaction point of gamma-rays within the detector. It will be used to in NuSTAR (FAIR) as part of the HIPSEC project where only 1pi solid angle coverage will be sufficient. A future up-grade to 4pi solid angle coverage will be required for future exploitation at, for example, SPIRAL2.

- **ISOL-UK Experimental equipment for HIE-ISOLDE and SPIRAL2 [2012-2017]**: develop and construct key apparatus to exploit state-of-the-art accelerated ISOL facilities coming online in 2012/2013, i.e. HIE-ISOLDE and SPIRAL2. Precision measurements of exotic nuclei properties; magic numbers, symmetries and nuclei produced in astrophysical processes such as the rapid proton capture process in proton rich nuclei.

- **EURISOL [2019+]**: Future flagship European ISOL project – requiring major target and beam developments at the limits, or beyond, of current technology. Successful UK involvement in this project requires the UK to develop expertise in measurements with intense ISOL type beams. In this regard the above ISOL-UK project is a key stepping stone.

  Technology development challenge: EURISOL will be the world leading ISOL facility. Here the beams will be produced by accelerating 1GeV protons directly onto a uranium carbide target with a power of 5 MW or using a 1 tonne mercury proton to neutron converter surrounded by fissile material. The construction of such high power targets and the associated radiological issues is a major challenge for the construction of the EURISOL facility. RAL has considerable experience in developing high power targets and have played an important role in developments at TRIUMF. The potential for involvement in the EURISOL is significant.

- **ELENA at Boulby underground laboratory [2012-2017]**: Underground accelerator laboratory for the measurement of key nuclear reactions at stellar temperatures (i.e. within the Gamow energy region) otherwise not feasible at surface laboratories.

- **PANDA-Dipole at FAIR, GSI [2010-2013]**: Address key aspects of Quantum Chromodynamics (QCD) e.g. the confinement of quarks in hadrons. High precision measurements of electromagnetic and hadronic charmonium
decays. Search for charmed exotic mesons and heavy glueballs. Measurement of time-like proton form factors, the determination of generalised parton distributions in hard exclusive reactions and the investigation of the transverse spin structure of the nucleon by measuring Drell-Yan processes.

- **PANDA-Cherenkov at FAIR, GSI [2014-2018]:** Enhancement of the physics reach of PANDA through the inclusion of the Disc DIRC.  
  *Technology development challenge: the development of a Disc shaped Detector of Internally Reflected Cherenkov light (DIRC) is a key element of the PANDA experiment. A PRD is currently funded to develop high-quality fused quartz plates and light-guides and a fast photon readout system for the disc DIRC capable of providing particle identification measurements. The development of a detector in the disc geometry is highly challenging. The full implementation is also a technological challenge.*

- **JLAB-upgrade Jefferson Lab US [2011-2015]:** Development of equipment matched to the 12 GeV upgrade of the electron beam energy at JLAB. Physics topics include; production of exotic or hybrid mesons and study of their properties - to study quark-confinement. Measurement of the three dimensional properties of the protons constituents – to determine the orbital angular momentum contributions of the quarks and gluons.

- **ALICE at LHC, CERN [2010-2018]:** The use of relativistic heavy-ion reactions to study the quark-gluon plasma – the state of matter an instant after the big bang.

- **Electron-Ion Collider (EIC) [2019+]:** Study of the quark-gluon structure of nucleons and nuclei in exclusive precision measurements in a high luminosity collider, e.g. the influence of the colour fields outside the nucleon and their role in the strong interaction on the nuclear-scale – responsible for binding nucleons in nuclei.  
  *Technology development challenge: High luminosity collider of polarised beams and a fast high-multiplicity 4π detector for exclusive coincidence experiments.*

- **Active Target NuSTAR, TRIUMF and HIE-ISOLDE [2013-2018]:** a novel multipurpose detector in which the gas detector acts both as target and detector simultaneously. The detector is based around the time projection chamber approach, i.e. capable of reconstructing tracks in the gas volume. To be used for a wide range of structure and astrophysics reactions at ISOL (e.g. HIE-ISOLDE, TRIUMF) and FAIR (R3B). This follows-on from the TACTIC PRD project.  
  *Technology development challenge: the TACTIC detector is a technology demonstrator. The major challenge is to scale up to a large active target detector capable of tracking particles of nuclear energies (MeV). The development of high density multisampling readout electronics capable of providing the sensitivity required for low energy high resolution measurements is crucial.*

- **ECOS [2020+]:** A European high intensity [100 µA] Stable Beam facility. It is recognised that topics such as the synthesis of superheavy nuclei (new elements) and the study of nuclear structure and shapes at the extremes of spin will require beam intensities well beyond present capabilities. ECOS will require the development of high power heavy-ion beams and targets that can withstand the beam power without disintegration.  
  *Technology development challenge: development of high power heavy-ion beam and target systems.*
Context: The following provides the background material required to understand the roadmap

**Nuclear Physics: The Physics of Strongly Interacting Matter**

Modern Nuclear Physics addresses fundamental issues relating to matter created within $10^{-5}$ s of the big bang through to the nature of strongly interacting matter in the current universe. It explores the emergent properties of matter from the basic interactions between quarks in baryons and mesons, to the shell structures of heavy nuclei such as uranium and how such nuclei may be synthesised in supernova explosions. It therefore connects intimately with basic research in Particle Physics and Astrophysics, and is highly pervasive technologically. As a discipline it examines 99.9% of the mass of the visible universe.

Understanding the nature of strongly interacting nuclear matter stands as one of the most challenging and most important scientific quests. This ambitious venture aims at building a fundamental description of nucleons starting with the individual quarks and gluons and ending with a description of nuclei and their structure. On the nuclear scale, this *ab-initio* approach sets out with a description of the nucleon-nucleon interaction and ultimately offers the possibility to predict the structure of nuclei. Most current models of nuclei use effective (as opposed to fundamental) interactions whose parameters are tuned to reproduce properties of stable nuclei in their ground-states. It has been found that the best test of these models and their underlying assumptions has been to measure nuclear properties at the extremes of; stability (the drip-lines), charge (superheavy nuclei), excitation and angular momentum. It is in these paradigms that the predictions diverge and will also form the ultimate tests of the *ab-initio* approaches. It is the challenge of exploring these entirely new physical domains that drives future UK Nuclear Physics research.

Remarkably, emerging from an apparently chaotic many-body problem, the nucleus can be described in terms of rather simple degrees of freedom, where nucleons move in non-chaotic orbits governed by their average interaction with all other constituents of the nucleus. Correlations between nucleons are manifest in pairing or ultimately rotational or vibrational modes where all nucleons act coherently. These simple modes are reflected in underpinning symmetries, which provide a characteristic experimental signature. At the limits of existence new structural modes have been observed, e.g. *halo nuclei* which possess a large volume of neutron matter with a compact core. Such systems provide sensitive tests of nucleon-nucleon correlations. In the future it is likely that even more exotic structures will be found.
Understanding the forces and symmetries driving these transitions and their connection to the strong interaction is of central importance.

At the sub-nuclear level, surprisingly, the structures of the proton and neutron remain undetermined. Whilst most textbooks would suggest a simple system composed of 3 spin 1/2 quarks, experimentally this is found to be far from the truth – only 30% of the proton spin arises from the spin of the quarks. The remainder is a ferment of gluons and virtual particles, which conspire together with the quark orbital motion to give a spin of 1/2 – how remains a mystery. New experiments with improved sensitivity are being developed to answer such questions. Similarly, why quarks are confined within hadrons remains to be explained. New experiments with improved sensitivity are currently being constructed. This challenge of describing nucleons within the framework of Quantum Chromodynamics (QCD) complements that of understanding the nucleus from the interaction of the constituent nucleons.

The most extreme test of nuclear matter occurs when nuclei collide at energies at which the energy density reaches 0.7 GeV/fm³ (5 times normal nuclear matter density). At such densities the nucleons dissolve into their quark constituents, undergoing a phase transition. This provides a laboratory test of the nature of matter a short instant after the Big Bang. A description of such a phase of strongly-interacting matter within QCD remains a challenge, as does its experimental characterisation.

Extremes of matter also occur in the cataclysmic death-throes of stars: supernovae. It is here that half of the elements above iron are synthesised, but exactly how is unknown. Generically the mechanism is referred to as the r-process, which encapsulates a series of rapid neutron-capture reactions. However, the question of the site of the r-process and if there is a single r-process, or many, remains to be answered. These reaction rates are so fast that the path proceeds through nuclei which are so neutron-rich, exotic, that they are not naturally occurring. Similarly, in environments where matter from one star is accreted on to the surface of a neutron star a series of rapid proton captures on radioactive nuclei, the rp-process, becomes the main source of energy driving an explosion. The nuclear physics of these reactions remains largely unexplored. Recent technical developments allowing these reactions to be accessed for the first time make this a high priority area. The understanding of neutron stars – from quakes to the details of the structure from surface to core – requires a determination of the nuclear Equation-of-State and the phases of nuclear matter. This endeavour is a key scientific challenge for Nuclear Physics.

Science Questions

Nuclear Physics is answering questions which define our understanding of systems from the largest (astronomical) to the smallest (hadronic) scale. The original 3 scientific questions from the NPAP report were (including the more specific sub-questions).

What are the Origins of the Elements?

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

What is the Nature of Nuclear Matter?

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

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

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

A more detailed exploration of the physics was provided in the NPAP report.

Science and Facilities

The origins of the elements: over half of the elements heavier than Iron are thought to be produced in the astrophysical r-process, an explosive series of rapid neutron capture reactions on highly neutron-rich radioactive nuclei. Observations of elemental abundances of elements in metal poor stars suggest at least two astrophysical sites for the r-process, with supernovae and neutron star mergers being candidates. In order to determine the astrophysical conditions in which the heavy elements are produced, it is essential to study the properties of highly neutron-rich nuclei lying along the path of the r-process. At the FAIR facility, it will be possible for the first time to produce large swaths of r-process nuclei. In the first phase of the FAIR project the decay properties of these nuclei will be measured, and in the second phase, using the new storage ring facility (NESR), the masses will be measured. These properties are the key to providing the link between the explosive astrophysical conditions heavy elements were created in, and the abundances of stable elements we observe today. Fragmentation beams are typically poorly defined both in energy and spatial size. The complementary ISOL approach such as HIE-ISOLDE, SPIRAL2 and TRIUMF ISACII provides spectroscopic grade beams. These will yield the ability to perform precision spectroscopy measurements on both neutron-rich r-process nuclei and proton rich nuclei associated with the rapid proton capture driving X-ray bursts. The structure of neutron stars is strongly linked to understanding the equation-of-state of nuclear matter, particularly neutron-rich matter. The key measurements here will be made by NuSTAR at FAIR.

Important projects in this area will be, NuSTAR (e.g. R³B and DESPEC) and ISOL-UK at HIE-ISOLDE and SPIRAL2. The UK community also has active exploitation programmes relevant to all the main nucleosynthesis sites - steady state burning, supernovae, novae and X-ray bursts. These activities will continue to exploit the opportunities at a number of international facilities, both stable and radioactive beams. One new opportunity that will open with UK involvement in FAIR is a detailed study of the r-process nuclei.
The Nature of Nuclear Matter: Key to understanding the nature of nuclear matter is examining nuclei at the extremes of stability, temperature and spin. Here the nucleus is beginning to reveal new types of structure, magic numbers and shapes. In many cases these quite unexpected results provide sensitive tests of our understanding of the nucleon-nucleon interaction inside the nucleus and of the most advanced nuclear models. To really understand these new modes, measurements must be made in nuclei significantly more neutron-rich than accessible at present. Advances will rely on facilities which can create nuclei at the limits and equipment with the sensitivity to probe them. The immediate investment at FAIR (R3B, HISPEC, DESPEC) and future investment at HIE-ISOLDE and SPIRAL2 (ISOL-UK) together with AGATA will ensure the UK makes a major scientific contribution. To improve the physics reach/sensitivity of the HISPEC, DESPEC and R3B projects upgrades to these projects are foreseen. The future storage-ring programme at FAIR will permit some of the most precise tests of nuclear structure (e.g. nuclear charge and matter radii) for the most exotic nuclei. Projects such as EXL and ILLIMA together with LaSPEC will be important in this regard.

EURISOL will be the “next generation” ISOL facility in Europe after HIE-ISOLDE and SPIRAL2. The ISOL-UK science and equipment programme provides a passport to the future science of nuclear structure and astrophysics.

Hardonic Properties and the Quark-Gluon Plasma: In order to understand the properties of hadrons and the nature of matter within QCD, in particular the contributions to the spin of the proton and nature of the quark-quark interaction, a series of measurements of generalised parton distribution measurements and studies of the spectroscopy of mesons and baryons will be performed at FAIR (PANDA) and JLAB (requiring the J-LAB) upgrade. Understanding of the influence of QCD on nuclei is a future goal of the Electron-Ion Collider (EIC). The properties of the quark-gluon-plasma, a state of matter which occurred an instant after the big-bang and is believed to reside in the core of neutron-stars and is formed in relativistic collisions between heavy-ions at the LHC – this will be studied using ALICE.

The Exploitation Programme

Roughly two thirds of the nuclear physics spend goes on science funded through the grants line, which uses a wide range of facilities dependent on the needs of the specific research programme. The current list of facilities is shown below. Over the next decade some will reach the end of their useful life, but many have significant upgrades planned or in progress which will ensure that they remain forefront facilities which the UK community will continue to exploit for specific research goals.

Current list of facilities being exploited by the UK.

- Argonne National Laboratory, US
- Australian National University (ANU), Canberra, Australia
- DESY, Germany
- Florida State University, US
- GANIL, France
- GSI, Germany
- ILL, Grenoble, France
- ISOLDE, CERN
- iThemba Labs, South Africa
- JAEA (Japan Atomic Energy Agency), Tokai, Japan
- Jefferson Laboratory, US
- Jyväskylä, JYFL, Finland

- Stable beams
- Stable beams
- Electron/positron beams
- Stable beams
- ISOL and fragmentation
- Fragmentation beams
- Reactor
- ISOL beams
- Stable beams
- Stable beams
- Electron/Photon beams
- Stable beams

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<tr>
<th>Location</th>
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<tr>
<td>Legnaro, Italy</td>
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<tr>
<td>Mainz, Germany</td>
<td>Electron/Photon beams</td>
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<tr>
<td>Max Lab., Lund, Sweden</td>
<td>Electron/Photon beams</td>
</tr>
<tr>
<td>Michigan State University, MSU, US</td>
<td>Fragmentation beams</td>
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<tr>
<td>Munich, Germany</td>
<td>Stable beams</td>
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<tr>
<td>Oak Ridge National Laboratory, ORNL, US</td>
<td>ISOL beams</td>
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<tr>
<td>Orsay, France</td>
<td>Stable/ISOL beams</td>
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<tr>
<td>RIKEN, Japan</td>
<td>Fragmentation beams</td>
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<td>Texas A&amp;M, US</td>
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<td>TRIUMF, Canada</td>
<td>ISOL beams</td>
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<td>Yale, US</td>
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**A European Long Range Plan**

In recent years there have been a number of influential reviews of Nuclear Physics within Europe (Nuclear Physics European Coordinating Committee [NuPECC], 2004 “Perspectives for Nuclear Physics in Europe in the Coming Decade and Beyond”\(^1\)). NuPECC is currently engaged in producing a new long-range plan which will be presented to the European Nuclear Physics community in Madrid at the end of May 2010. It is believed that the above roadmap for Nuclear Physics is strongly aligned with what will be proposed in the long range plan. However, the UK roadmap may evolve to reflect emerging European priorities.

\(^1\) [http://www.nupecc.org/pub/lrp03/long_range_plan_2004.pdf](http://www.nupecc.org/pub/lrp03/long_range_plan_2004.pdf)