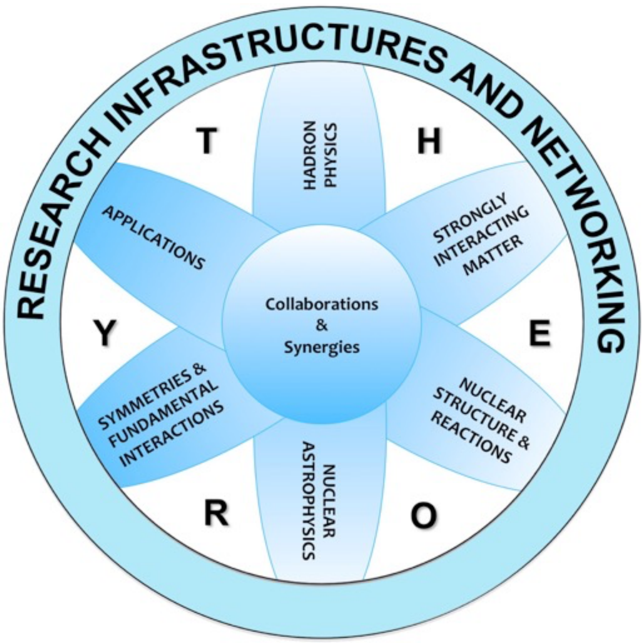
NuPECC LRP2024 Executive Summary

Introduction

What does Nuclear Physics stand for?

Nuclear physics is the study of the atomic nucleus, its constituents, structure, and behaviour. It is a key basic scientific field that investigates the properties of matter at the subatomic level. This domain of research affects not only our fundamental understanding of nature but also has many peaceful applications in all areas of modern life. Nuclear physics research originally started in Europe in the late 19th century. Now, in the 21st century, Europe is still at the forefront of nuclear physics research and applications. This leading European role is due to a rich and diverse landscape of research institutions and infrastructures in all European countries.
The present Long Range Plan for European nuclear physics summarizes progress in the field in the last decade, provides an outlook on expected developments in the next decades, and presents recommendations for scientific institutions, policymakers, and research funding organizations.

Modern nuclear physics is made up of a wide range of subfields, such as hadron physics, strongly interacting matter under extreme conditions, nuclear structure and reactions, nuclear astrophysics, fundamental interactions and symmetries, and nuclear science applications.



The main domains of nuclear physics and their interlinking with theory, collaborations, infrastructures, and networking

The goal of nuclear physics and, more broadly, nuclear science is to comprehend the fundamental forces of nature that underlie phenomena involving the atomic nucleus and its constituents. To be more specific, the research program is guided by the search for answers to the following scientific questions and challenges:

- How does the majority of the visible mass of the universe emerge from the almost massless quarks?

- What are the properties of the quark-gluon plasma, which is the qualitatively novel state of nuclear matter at extreme conditions of temperature and density?
- What can Nuclear Physics teach us about the limits of the Standard Model of Particle Physics?
- How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
- What are the limits of the existence of nuclei, and what phenomena arise from open quantum systems?
- What shapes can nuclei take, how do nuclear shells evolve, and what role do nuclear correlations play?
- What are the mechanisms behind nuclear reactions and nuclear fission?
- What is the role of the strong interaction in stellar objects?
- How can we better understand the synthesis of heavy elements and the chemical evolution of the visible universe?
- How might Nuclear Physics strengthen its role in society's sustainable development?

Nuclear Physics and Society

The United Nations adopted the 2030 Agenda for Sustainable Development in 2015 to secure peace and prosperity for people and the planet. The agenda comprises 17 Sustainable Development Goals (SDGs). Those are meant as a call for action to all governments across the globe, but also research communities can make a significant contribution.
Nuclear physics and its applications in Europe play a major role in the domains of energy #7, health #3, and space #9. The field of nuclear physics, with its educational, political, and economic influence, can support numerous overarching objectives, including #4 high-quality education, #5 gender equality, and #10 decreased disparities, #12 responsible consumption and production, and #13 climate action. Nuclear physics techniques such as isotopic markers to study plants and the water cycle have strong effects on #2 (zero hunger), #6 (clean water), #14 (life below water), and #15 (life on land). The responsible treatment of nuclear waste from medical and energy applications addresses #11 (sustainable cities) and #12 (responsible consumption). The nuclear physics-based monitoring of non-proliferation aims to address #16 (peace). Finally, the strong collaborative nature of nuclear physics in particular in Europe supports #17 (partnership).

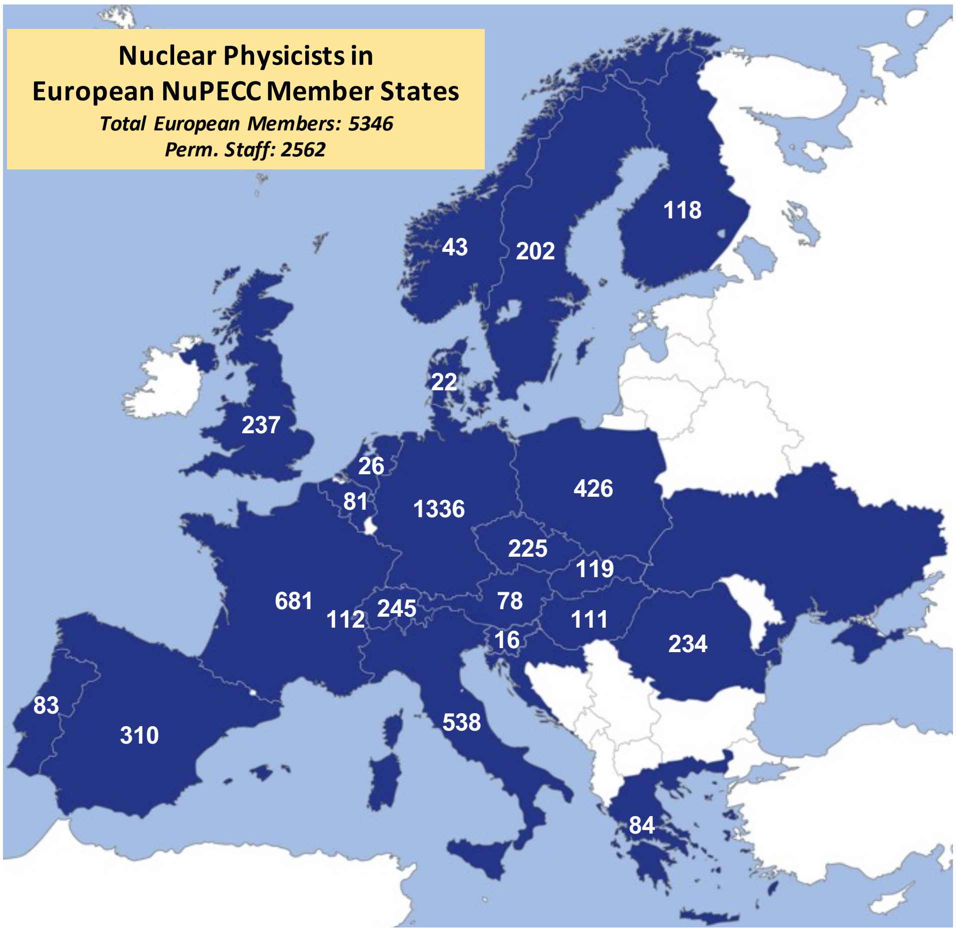
Sustainable Development Goals (SDGs) of the United Nations, among which nuclear physics makes the largest contribution.

Thus, nuclear science and technology have benefited human progress, culture, and our understanding of our delicate environment in general, as well as health, economic growth, and security in nations all over the world. The overall impact of nuclear science on the environment and society is a subject of the NuPECC 2022 report "Nuclear Physics in Everyday Life".

European landscape of nuclear physics

People

According to a recent NuPECC survey, more than 5300 scientists are working in nuclear physics in Europe. Of them, 1200 work on nuclear physics theory and 4100 on experimental nuclear physics. There are approximately 1800 PhD students, 1000 post-docs, and over 2500 scientists with permanent positions.

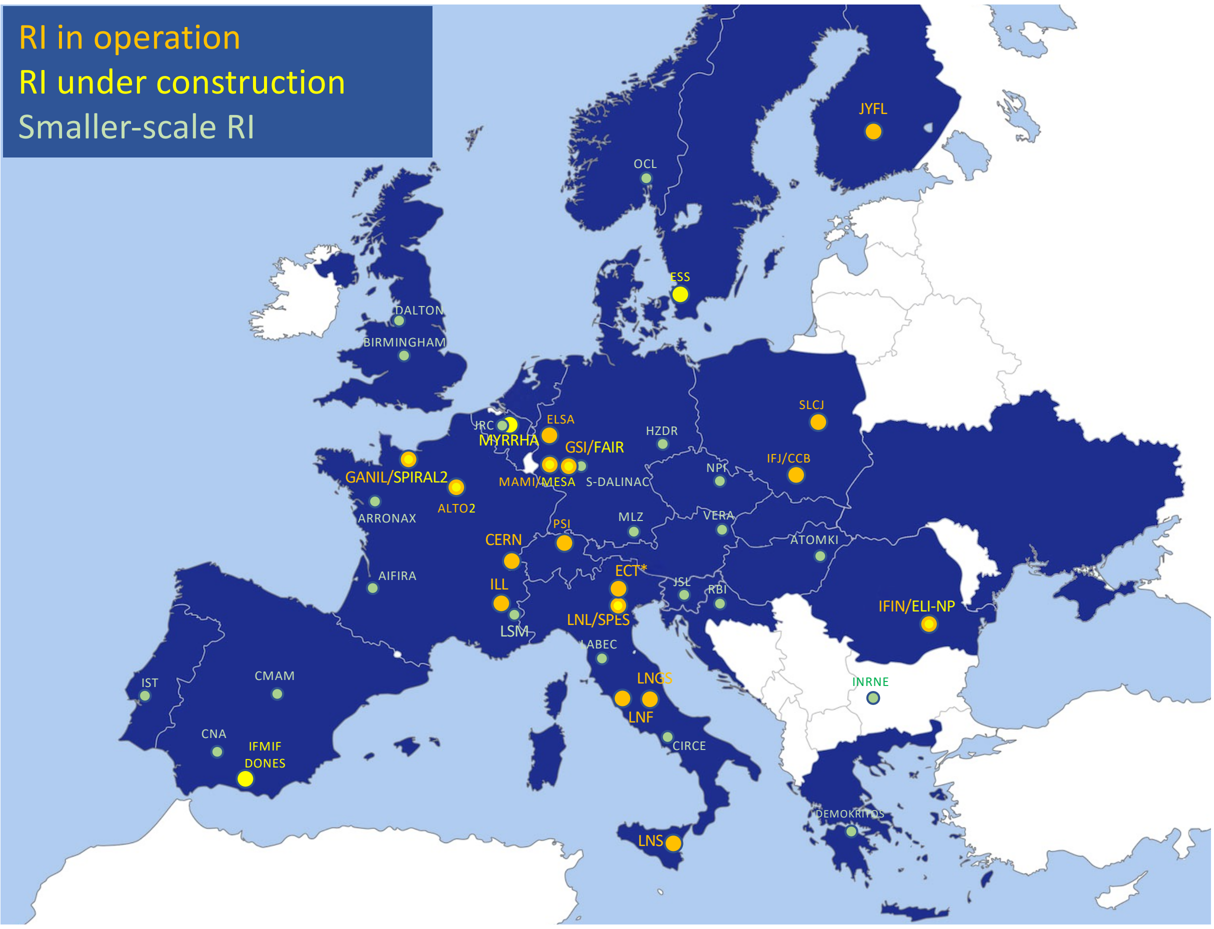


Nuclear physicists in the European NuPECC Member countries and the Associated Member CERN.

It is of utmost importance to inspire and invest in the next generation of nuclear scientists, drawing on the talent and potential of the entire society. This is essential, not only within nuclear physics but as capacity building across the wide range of disciplines and impact areas relying on the nuclear sciences. The investment of European funding bodies and institutions in nuclear physics is essential to inspire the public about nuclear science and its impacts; educate and train the next generation of nuclear scientists; and support equitable career progression with an inclusive approach to diversity across academic, industrial, and vocational career paths.
To further develop the pool of knowledge for future generations in nuclear science, the nuclear physics community explores these areas of knowledge, ensures their understanding and development, and also communicates them to – and develops them jointly with – the next generations, through outreach, education, and training.

Infrastructures

The scientific questions and challenges are answered by the European Nuclear Science community by carrying out experimental and theoretical investigations within a rich ecosystem of research infrastructures and institutes of varying sizes, ranging from ESFRI-scale facilities to small university departments. Each area of this ecosystem has an important role to play in the delivery of Nuclear Science in Europe. The landscape of European Research Infrastructures is shown in the figure below. The huge range of Nuclear Science phenomena and applications presented in this Long Range Plan requires, in turn, a very large range of facilities. These facilities offer both stable and radioactive ion beams, electromagnetic probes, neutron sources, elementary particles, computing infrastructure or other instrumentation essential to delivering our Nuclear Science. Some of them offer low-energy beams with dedicated characteristics for analysis and applications. Others produce unique short-lived radioactive nuclei, explore the high-energy frontier of nuclear physics or provide high-intensity beams to explore rare nuclear processes. All these types of facilities find their natural place in the European research landscape and are needed. Often, access to these Research Infrastructures is facilitated by EU-funded programmes, such as STRONG2020, EURO-LABS, RADIATE, RADNEXT, … Such programs guarantee that all potential users can gain access to state-of-the-art facilities, irrespective of status.
All sub-fields of nuclear physics extensively exploit several large-scale and more than 15 smaller-scale infrastructures in Europe. Among them, large infrastructures from the European Strategy Forum for Research Infrastructures (ESFRI) Roadmap play a particularly important role in federating and shaping nuclear physics research and the scientific community.



European landscape of nuclear physics infrastructures.

Recommendations for Nuclear Physics Infrastructures

The NuPECC Long Range Plan 2024 resulted in the following main recommendations for infrastructures of importance for nuclear physics:

- The first phase of the international **FAIR** facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. The completion of the full facility including the program of **APPA**, **CBM**, **NUSTAR** and **PANDA** should be vigorously pursued as it will provide European science with world-class opportunities for decades.
- At **GANIL/SPIRAL2** the Super-Separator Spectrometer **S^3** is in an advanced stage of completion and the low-energy **DESIR** facility and heavy-ion injector **NEWGAIN**~~,~~ will be operational from 2027/28. The refurbishing of the cyclotrons will ensure their operation for the next decades. Timely completion and full exploitation of these GANIL/SPIRAL2 projects should be vigorously pursued. The future evolution of the facility towards a very high-intensity reaccelerated RIB facility of up to 100 MeV/u should be actively planned.
- Nuclear physics opportunities at **CERN** constitute a world-leading research programme that has successfully diversified CERN's scientific reach. The construction of **ALICE 3** as part of the **HL-LHC** plans is strongly supported. New initiatives should be sought to maximise the scientific exploitation of **ISOLDE and AD/ELENA**. As the roadmap for the post-LHC future of CERN is developed, a strategy should be prepared to secure future opportunities for continuing world-leading nuclear-physics programmes that are unique to CERN.
- At **ELI-NP** studies will focus on addressing key topics, such as laser-driven ion and electron acceleration. Implementing the gamma beam system to achieve the full completion of the facility to allow breakthrough results in the field of nuclear photonics is of high importance.
- Continuing co-ordinated efforts in developing the **ISOL facilities** in Europe, such as **ALTO, IGISOL, ISOLDE, SPES, and SPIRAL** will be key to maintaining their world-leading position in many areas of radioactive isotope science. Extending these efforts towards future facilities, such as **ISOL@MYRRHA, TATTOOS@PSI,** and **RIB@IFIN**, together with the development of common instrumentation, will secure the European leading position for radioisotope production, separation, and acceleration techniques, and create new avenues for the future and should therefore be actively pursued.
- Large-scale **stable beam** facilities, such as **FAIR/GSI**, **GANIL/SPIRAL2, IFIN, JYFL, LNL, LNS, NLC**, and smaller ones, such as underground facilities and AMS systems, should be optimally exploited. Developments of novel and more intense beams and capabilities are also recommended to open new opportunities for basic science and applications. It is recommended that synergies between all these facilities, irrespective of size, be reinforced.
- Exploitation and optimisation of the European **lepton beam facilities**, including **ELSA, MAMI, and S-DALINAC**, are needed to realise their full physics potential. The completion of the **MESA** facility and the **High-Intensity Muon Beams** project at **PSI**, as well as the optimisation of the **M2 Muon Beam Facility** at **CERN**, are recommended.
- Neutron facilities that are producing unique experimental results in nuclear fundamental research and applications, like **ILL,** and **n_ToF at CERN**, should be kept in operation. The **NFS** facility at SPIRAL2 has begun providing a very high neutron flux of fast neutrons and should attract a broad scientific community. **ESS** and the future

infrastructure **IFMIF-DONES** will provide advanced tools for interdisciplinary research and their unique capabilities to serve advances in nuclear physics should be explored.

- Theory centres and groups should be strongly supported throughout Europe, in particular the **European Centre for Theoretical Studies (ECT*, Trento, Italy)**, which is a unique European centre dedicated to theoretical nuclear physics in the broadest sense. The activities of ECT* are complementary in scope to those at existing research facilities based at universities or experimental laboratories.

- Collaboration with **non-European infrastructures** should be fostered in all areas of nuclear research to seize unique scientific opportunities and synergies that complement scientific programmes based in Europe. In particular, European participation in the construction of the **ePIC** experiment at the future international flagship facility **EIC** is recommended.

International and Interdisciplinary Context

Nuclear Physics is embedded in the landscape of the European Research Area (ERA). Close collaboration with neighbouring fields of science, in particular with particle and astroparticle physics communities in a framework of Joint ECFA-NuPECC-APPEC Activities (JENAA) resulted in several new initiatives like JENA Seminars, specialized working groups and Expressions of Interest on various research topics of joint interest.

The research in Nuclear Physics is a worldwide effort and the European nuclear physics community is strongly involved in scientific programs at overseas laboratories in North America (US and Canada), Asia (China, India, Japan and Korea) and South Africa. The exchange of information and tightening of collaborations between international partners is facilitated through associated membership in NuPECC of the research infrastructures CERN, RIKEN Nishina Centre from Japan, and iThemba Labs from South Africa and the country of Israel as well as the status of permanent observers in the Committee of the sister organisations: ALAFNA from South and Latin America, ANPhA from Asia CINP from Canada, and NSAC from US. In the international context, the important role of integration of the nuclear physics community across continents plays IUPAP with its Commission 12 on nuclear physics and Working Group 9 on nuclear physics research infrastructures.

Further fast and equilibrated development of nuclear physics in Europe will require investment in people, infrastructures, experimental techniques and theoretical approaches. Each sub-field of nuclear physics has its specific priorities and requirements leading to recommendations specified in the following parts of the Executive Summary.

Fundamental Nuclear Physics

Hadron Physics

The goal of hadron physics is to understand the rich and complex features of the strong interaction. How does the major part of the visible mass of the universe emerge from the almost massless quarks? Can massless gluons form massive, exotic matter? What is the role of strong interactions in stellar objects, and in precision tests of the Standard Model? Answering these questions requires a diverse set of experimental and theoretical approaches. At present, European hadron physicists conduct experiments at facilities within and outside Europe, with great success. These facilities, their planned upgrades, and the approved flagships PANDA at FAIR, Germany and ePIC at EIC, USA, open new avenues for ground-breaking discoveries.

Existing facilities: We recommend the continuing support of the successful hadron physics programs in Europe and the participation of European groups at global facilities. Particularly important hadron physics facilities are

- **AMBER** at CERN
- **ELSA** in Bonn, **HADES** at **GSI, MAMI** and **MESA** in Mainz, Germany
- **Jefferson Laboratory** in Newport News, USA

Furthermore, we recommend the support of ongoing hadron physics activities at the multi-purpose facilities Belle II, BESIII and the LHC.

Future flagships: We recommend the expedited realisation of the antiproton experiment PANDA, and the support of European groups to contribute to the electron-ion experiment ePIC. By virtue of their different beam species and energy regimes, PANDA and ePIC will explore complementary physics aspects. In a ten-year perspective, these two next-generation experiments must be made ready to launch.

- **PANDA**: The physics program, including the prospect of unravelling exotic matter, remains unique and compelling. PANDA will strengthen the European position on the global scene and act as a unifying force for the community. Therefore, we recommend support for its construction and for the development of instrumentation, software and analysis tools.
- **ePIC**: Here, European researchers will be able to explore unknown features of quarks and gluons inside nucleons and nuclei. We recommend supporting the participation of European groups in ePIC and reinforcing scientific and technological activities which synergize with European projects.

Theory / Computing:

- Theorists play an essential role not only in interpreting hadronic physics experiments but also in providing input and predictions for new experiments, particularly in the challenging transition between quark/gluon and hadronic degrees of freedom. Support for theoretical groups in terms of positions and career prospects is thus essential for progress in hadron physics.
- To match experimental progress, sophisticated approaches need to be developed. In lattice QCD, the rapid evolution of computational techniques and hardware calls for new algorithms and software. We recommend the support of theory groups at universities and research centres to prepare the community to benefit from the European investment in supercomputing and quantum computing.

Strongly Interacting Matter at Extreme Conditions

Ultra-relativistic heavy ion collisions aim at producing and studying the quark-gluon plasma (QGP), which is the qualitatively novel state of nuclear matter at extreme conditions of temperature and density. Different collision energies realize the QGP at different temperatures and densities. The experimental focus is discovering in microscopic detail the material properties of the QGP at the highest temperature reached at the LHC, and to find the expected onset of the first-order phase transition at finite baryon density at FAIR. Given the long timescales necessary for the R&D and construction of these experiments, a sustained research effort is required to advance the development of the next-generation experiment in parallel with the ongoing exploitation of existing facilities and detectors. The priorities in this multi-pronged endeavour can be summarized as follows:

- **Future flagship facilities and experiments**
  - **ALICE 3** at **CERN** is a completely new dedicated high-energy nuclear physics experiment based on innovative detector concepts that will be essential for continuing

after 2035 a scientifically leading role of Europe in high-energy nuclear physics. The programme relies on innovative R&D that will benefit neighbouring fields of nuclear and particle physics. Strong support for R&D should be given to maintain the opportunity of installing ALICE3 for Run 5 at the LHC.
    - To investigate nuclear matter at high baryonic density, the timely completion of **SIS-100** at **FAIR** and the realization of the **CBM** experiment are of utmost importance. Efforts should continue to support R&D activities related to advanced **CBM** silicon vertexing and tracking devices.
    - To exploit physics opportunities at the **CERN LHC** after 2035 (Run 5 and 6), the **LHCb Upgrade2** and the fixed-target setup will have a strong impact on the heavy ion programme. **ATLAS** and **CMS** will play an important role in the characterization of high-momentum transfer processes up to the end of the LHC programme in Run 6.
    - The **NA60+** detector at the **SPS** will address the remaining open questions in the electromagnetic and charm sector at the SPS with unprecedented event rates. R&D and construction for this detector deserve strong support.

- **Support of existing facilities and experiments**
    - To maximise scientific output from the significant investment in current detector upgrades at the **LHC**, the continuation of the heavy-ion programme with Runs 3 and 4 (up to 2029) should receive full support. Timely support for the further **ALICE** upgrades in long shutdown 3 will provide a unique opportunity to enhance the physics reach in Run 4.
    - With its Upgrade I detector and with the new particle-identification subdetectors to be installed during long shutdown 3, **LHCb** is equipped to pursue a unique fixed target program at the LHC and to perform competitive measurements for Pb-Pb systems in collider mode. The exploitation of these opportunities should receive full support.
    - The full exploitation of the existing detectors and facilities, in particular **HADES** and **R3B** at **SIS-18/SIS-100**, should receive full support.
    - The full exploitation of **NA61** at **SPS** should be carried out.

- **Theory developments**
    - Theoretical work in the field of heavy-ion collisions should be guaranteed continuous support, both in its phenomenological aspects (theoretical support needed to interpret the results and to provide feedback to the experimental programme) and from first principles (quantum chromodynamics).
    - Collaboration that strengthens the relation between heavy-ion physics and neighbouring fields including astrophysics and particle physics, that connects to novel ways of computing and data analysis, or that improves the interplay between theory and experiment should be particularly encouraged and nurtured.

Nuclear Structure and Reaction Dynamics

The main challenges in Nuclear Structure and Reaction Dynamics in the next decade are the following: How do nuclei and nuclear matter emerge from the underlying fundamental interactions? What is the limit of nuclear existence and which phenomena arise from open quantum systems? How are nuclear shells evolving across the nuclear landscape, what kind of shapes nuclei can take, and what is the role of nuclear correlations? What are the mechanisms behind nuclear reactions and nuclear fission? How can we probe the equation of state with nuclear structure observables, such as resonances? How can nuclear structure and reaction dynamics contribute to astrophysics, hadron physics and fundamental symmetries?

- **Support of existing facilities and experiments**
    - To ensure complementarity in experimental programs, it is essential to strongly support *large- and small-scale facilities* which guarantee access to the whole community, allow

detector testing and exploratory experiments in preparation for more complex future experiments, and play a key role in the training of new generations of physicists.
  - The coordinated effort amongst the **ISOL facilities** in Europe has been key to securing a world-leading position in many areas of radioactive beam science. Reinforcing this collaboration on radioisotope production, separation, and acceleration techniques, together with the exploitation of common instrumentation and a stream of new ideas, will secure the leading position of Europe in the future.
  - To push the frontiers of spectroscopy and lifetime measurements at the limits of energy and production, superb resolution and high efficiency for gamma-ray spectroscopy is essential. It is therefore mandatory to recommend the full completion of the European flagship gamma spectrometer **AGATA-4π** (with ancillaries) which is and will stay the major workhorse for nuclear structure gamma-spectroscopy and nuclear astrophysics precision physics, at both radioactive and stable ion-beam facilities.

- **Future flagship facilities and experiments**
  - Unique insights into Nuclear Structure and Reaction Dynamics can only be obtained via the urgent completion of the **FAIR** facility (including the Low-Energy-Branch), **SPIRAL2**, **SPES**, **ELI-NP**, **ISOL@MYRRHA**, and **ISOLDE upgrades**, as unique laboratories for studying reactions of very exotic nuclei, and for the exploration of the nuclear chart towards the driplines.
  - The world leadership of Europe in the use of heavy ion storage rings - as key precision instruments for the study of nuclear masses and radii, nuclear resonances, isomers, reactions and fission - should be maintained by the construction of **future rings at FAIR and HIE-ISOLDE**.

- **Theory developments**
  - It is mandatory to establish efficient interfaces between theories based on different degrees of freedom, to assess and reduce theoretical uncertainties, to improve the efficiency of many-body methods for a good description of spectroscopic observables, to improve time-dependent methods and reaction calculations, and to advance methods like Bayesian inference in combination with new computational techniques (e.g., Artificial Intelligence, Quantum Computing).
  - Nuclear theory is crucial for interpreting experimental results and guiding future research. Excellence programs to train, attract and keep talent within the field should be pursued. Theory centres should be strongly supported throughout Europe, in particular the **ECT*** and emerging virtual access facilities, which provide theory results for experimentalists (e.g., the Theo4Exp VA facility in the **EURO-LABS** project).

Nuclear Astrophysics

Nuclear astrophysics comprises the study of nuclear processes in astrophysical objects such as stars, covering the wide range of physical scenarios found in space. Traditionally, nuclear processes have been the underlying scientific link between different observations of the same object. For example, our Sun has only in the last years seen tremendous progress in the understanding of the processes from its core to its atmosphere.

Multi-messenger astronomy from binary neutron star mergers, and potential new kilonovae powered by the radioactive decay of r-process nuclei, will pose a challenge both for nuclear theory and experiments, as well as for astrophysics modelling. To achieve a better understanding of the heavy-element synthesis and chemical evolution in the Cosmos, a theoretical description of fission, nuclear properties far from stability and neutron-capture rates are needed. Experimentally, physicists in Europe should have access to radioactive beam facilities at the frontier of exotic nuclei research. While nuclear physics is essential to interpret the anticipated forthcoming observations, future gravitational-wave detections at LISA and the Einstein Telescope can also advance the frontiers of nuclear and hadronic physics by carrying information on the dense nuclear matter and its equation of state. As a multidisciplinary research area, nuclear astrophysics must support as well key initiatives in observational and theoretical astrophysics, and cosmochemistry, and when possible, actively participate in the definition of new supercomputers, extremely large telescope projects, and high-energy space-borne observatories (e.g., eXTP, e-ASTROGRAM).

- Due to its interdisciplinary nature, nuclear astrophysics research greatly benefits from the support given for joint research activities and networks in Europe. We highly recommend to continue strengthening nuclear astrophysics networks in Europe (e.g. **ChETEC** and ChETEC-Infra) and securing their funding. Such networks are also a key to maintaining and strengthening the links to international nuclear astrophysics collaborations e.g. to the U.S. and Japan.

- **Support of existing facilities and experiments**
    - Small-scale facilities are important for nuclear astrophysics research and the activities connecting their work such as direct measurements to the lowest possible energies, as well as indirect measurements, should be further supported.
    - European underground laboratories (**LNGS Bellotti Ion Beam Facility** and **Felsenkeller**) play an essential role in nuclear astrophysics and should be supported.
    - the storage rings, **CRYRING** and **ESR@FAIR** open important physics cases for nuclear astrophysics and should be fully exploited.

- **Future flagship facilities and experiments**
    - Radioactive beam facilities in Europe (in particular the **Super-FRS** at **FAIR**, including the Low-Energy-Branch, the upgrade of **ISOLDE**, and **SPIRAL2**) will be essential for studies of exotic nuclei involved in various astrophysical processes. We strongly recommend the completion of the ongoing construction and upgrades at these European large-scale facilities.
    - A large (> 10MV) **AMS** system is currently missing in Europe and its construction should be considered. It will provide the high abundance sensitivity required, e.g., for the most demanding astrophysical applications. For example, isotopic variations in meteorites are one of the major current challenges that need to be addressed and require dedicated measurements.

- **Theory developments**
    - To achieve a better understanding of the heavy-element synthesis and chemical evolution in the Cosmos, microscopic models for nuclear structure, decays and reactions are needed with a special emphasis on the description of neutron-capture rates, beta decays, fission properties of exotic nuclei as well as the equation of state of dense matter.
    - Access to large and fast **HPC** facilities in Europe is essential to perform heavy microscopic nuclear physics calculations as well as astrophysics simulations with improved numerical resolution, advanced neutrino transport methods, and the inclusion of rotation and magnetic fields.
    - Because diverse aspects of the nuclear theory are involved in astrophysics modelling, the **ECT*** in Trento is an essential place for training and networking in nuclear astrophysics.

Symmetries and Fundamental Interactions

Fundamental interactions and symmetries can be studied by powerful low-energy probes. As such, precision measurements are complementary to collider searches for new physics. Pioneering techniques are under development to produce, manipulate, cool, and trap a diverse range of particles, including radioactive nuclei, neutrons, antiprotons, pions, muons, exotic atoms, and highly charged ions. Also, the development of low background, ultra-high resolution spectroscopy techniques is essential. Low energy, precision experiments require dedicated efforts and often depend on access to extended beam times at our research facilities.

- **Support of existing facilities and experiments**:
  - The multidisciplinary research infrastructures **ILL, FRM-II and PSI** provide unique opportunities for fundamental physics at their cold and ultracold neutron beamlines. Their efforts for infrastructure upgrades should be supported. The long-term operation of ILL should be ensured beyond 2033.
  - Continued support should be granted for the development and commissioning of facilities for the production, storage and trapping of heavy highly charged ions, such as **ESR**, **CRYRING** and **HITRAP** at **GSI/FAIR,** and high-energy **EBIT** at other laboratories.
  - The long-term support from **CERN** to the **AD/ELENA** physics program should be matched with support to running experiments, planned projects, and potential new proposals.
  - In general, customised instrumentation and beam time availability should be guaranteed for fundamental tests at RIB facilities like **ISOLDE**, **GANIL-SPIRAL2**, and **JYFL ACCLAB/IGISOL**.
  - **Direct neutrino mass measurements** will soon be limited by systematic uncertainties. To overcome this limitation**, cross-disciplinary efforts** aimed at integrating available and novel technologies should be supported. Multiple and **complementary experimental searches** of neutrino-less double beta decay have to be encouraged as they can reach into the inverted hierarchy in the next decade.

- **Future flagship facilities and experiments:**
  - **Specialization** of upcoming Radioactive Ion Beam facilities such as **ISOL@MYRRHA** and **DESIR at GANIL-SPIRAL2** should be regarded as an opportunity not to be missed.
  - The **HIMB upgrade** at **PSI** will allow for improved measurements and new experiments in both fundamental and applied physics with muons. The project should be vigorously pursued and executed to allow for these exciting new possibilities with the first beam expected in 2028.
  - At **ESS**, a fundamental neutron physics beamline should be installed as soon as possible.
  - The future **CR** and **HESR** at **FAIR** would provide unique opportunities by extending the storage ring programs with highly charged ions to high energies and, therefore, their realization should be vigorously pursued.

- **Theory developments**
  - Initiatives to develop an inclusive theoretical framework fostering sustainable connections between nuclear theory, quantum chemistry, atomic and molecular physics, and particle physics must be encouraged and vigorously supported. They are essential for the emergence and application of new powerful probes, including radioactive molecules, thorium clock, or quantum-logic spectroscopy in highly charged ions. In parallel, efforts should be directed towards enhancing the precision of traditional probes, like the determination of V_{ud} in nuclear beta decay, which is currently limited by theoretical uncertainties.
  - To enhance the discovery potential of various experiments, a precise theoretical description of different nuclei is essential. For example, improved sensitivities of QED tests in highly charged ions and exotic systems require improved knowledge of nuclear polarization. Another key challenge concerns rates of neutrinoless double beta decays, which directly relate to nuclear matrix elements. Theoretical predictions obtained with nuclear structure models should be validated by employing the same models to reproduce experimental electroweak-interaction benchmarks.

- The strong interdisciplinary program of the **ECT*** in Trento, which should be strongly supported, provides a unique meeting ground for members of the various fundamental-symmetry subcommunities.

Applications and Societal Benefits

To ensure peace and prosperity for the people and planet, the United Nations adopted in 2015 the 2030 Agenda for Sustainable Development, which led to 17 Sustainable Development Goals (SDGs). Those are meant as a call to action for all the governments across the globe, but also for all research communities to contribute. Nuclear science has to critically assess where it can contribute to those and to engage fully in those opportunities. The nuclear science community addresses directly (#3 Good health and well-being, #7 Affordable and clean energy, #9 Industry, innovation and infrastructure, #13 Climate action) or indirectly (#4 quality education, #5 gender equality, #10 reduced inequalities) some of the goals through innovative and collaborative approaches. We highlight here how nuclear science in Europe can have the highest impact.

- For nuclear applications that will have societal relevance for the foreseeable future, it is indispensable to continue to work on **improving nuclear data**, including both the measurement and the evaluation of nuclear data. Those are needed to support research in the fields of energy, health, space, and material science.
- The interdisciplinary nature of nuclear science applications needs a workforce with a diverse background. This requires **capacity building** in the fields of radiochemistry and radiobiology, as well as maintaining nuclear application competencies in Europe. For this purpose, it is essential to maintain and develop the landscape of smaller-scale facilities, in coordination with the large-scale facilities, which are crucial for nuclear applications.
- The large array of nuclear application research fields requires **adapted beam access models** that reflect the dynamic developments in their fields. An adequate funding for the present smaller and large facilities, as well as auxiliary platforms, are required for health, space, heritage science, and materials research applications.
- New generations of nuclear energy sources and the management of nuclear waste through partition and transmutation, depend on sustained technological developments in the present facilities, as well as the **completion of MYRRHA and IFMIF-DONES.**
- The potential of novel medical radionuclides can only be realized by upscaling the production capacity in Europe to clinically relevant activities. This should be achieved through the **enhanced use of the MEDICIS separator** at CERN, the **expansion of the PRISMAP project**, and the **completion of the medium and high-energy accelerators and radionuclide mass separators ISOLPHARM** at **SPES**, **ISOL@MYRRHA**, **IMPACT-TATTOOS** at **PSI**, and **SMILES** at **Subatech**.
- Europe's capacity in space dosimetry, radiobiology, and radiation hardness testing requires the sustained effort of the present irradiation facilities, as well as the completion of the first galactic cosmic ray simulator **in Europe at GSI/FAIR**.
- There is an increased need for **isotope-sensitive techniques** in environmental, heritage, and material science for which a sufficient capacity should be ensured. This can be achieved through the sustained operation of research reactors for neutron activation analysis, improved sample preparation, novel technologies (e.g., ICP-MS-CRIS, MIXE), the improvement of the present **AMS** facilities. The installation of a high-energy **AMS** in Europe (>10 MV) is recommended.

Nuclear Physics Tools

Advancement in the understanding of fundamental physics is deeply related to the progress in the tools for experimental and theoretical investigations. These tools intervene in detector R&D, detector operation, data acquisition and analysis, theoretical interpretation of experimental results and genuine theoretical developments. The tremendous progress in the field of Nuclear Physics has led to the pressing need of appropriate numerical tools aimed at addressing the most relevant experimental, theoretical, and technological challenges, such as those encompassed by the Joint ECFA-NuPECC-APPEC (JENA) initiatives. To this end, the advent of algorithms based on Machine Learning (ML) and Artificial Intelligence (AI) techniques, and the fast progress in the field of Quantum Computing (QC) have opened an entire new world of possibilities.

Detectors and experimental techniques

The efforts in the detector R&D in nuclear physics should be reinforced as follows:

- An elaboration of a roadmap for detector R&D dedicated to the specificity of low-energy nuclear physics and applications in radiation monitoring and heritage science must be supported.
- Strengthening of the collaborative effort in developing cutting-edge detector technology for identified applications in accelerator experiments with respective activities in high-energy particle physics and other adjacent research fields.

Building new expertise, training of the next generation of detector R&D experts and strong collaboration with industry are vital and indispensable for the continuous development and sustainability of the manifold tools for the European nuclear science community. This is also one of the major goals of projects within the programme Horizon Europe of the European Union. It has to be pursued and supported with the highest priority as an integrated building block of all scientific and technological activities.

The following strategic actions are needed to ensure the continuation and progress of experimental nuclear physics in Europe:

- Cutting-edge developments in the overall read-out chain, from front-end ASICs to the DAQ, to the use of heterogeneous computing resources and advanced algorithms, also exploiting artificial intelligence techniques;
- Enhance precision and efficiency in high-resolution laser spectroscopy and mass spectrometry, for studying the structure of rare isotopes and testing fundamental symmetries. Improve existing ion-trap setups, ion manipulation and decay detection techniques for these experiments.
- Establish infrastructures to ensure the provision of stable and radioactive targets, as the dedicated mass separator for providing radioactive samples and targets – foreseen to be built at PSI.
- Europe needs to secure a strategic supply of stable enriched isotopes for fundamental research and applications as is the case for the installation of a European Electro-Magnetic Ion Separation facility, providing material of the highest enrichment in rare stable isotopes;
- In some areas of experimental nuclear physics, the following specific actions are recommended:
  - Realization of polarized frozen spin targets and high-performance jet targets used inside accelerator rings;
  - Continue the production of lead tungstate crystals.
  - The scope of radioactive molecule production and research should be broadened across Europe to enable this growing field of research.

The ever-growing demands of future nuclear physics experiments require a continuous and focused R&D activity with the following aims:

- Enhance the performance, radiation hardness and environmentally friendly features of the current detector technologies based on gaseous and solid sensing materials;
- Develop novel efficient neutron detectors to replace those based on ^{3}He;
- Develop new materials for scintillators, p-type segmented Germanium detectors and new particle identification techniques.

Numerical tools, techniques and resources

- **Develop, maintain and disseminate optimized algorithms and codes.** Promote freely available software packages used by international collaborations. Encourage structured software collaborations. Develop interfaces between system software layers designed by IT experts and core software produced by nuclear physicists. Provide adequate funding for software development.
- **Provide long-term career perspectives for software developers in the field.** Acknowledge the growing need for software developers and IT experts. Strengthen this community by training early-career researchers. Enable institutional recognition through awards and career advancement.
- **Educate and train in software development.** Encourage collaborative software development through the usage of code versioning, containers technologies, CI/CD, AI/ML, workflow management, etc.
- **Invest in software frameworks.** Create multi-architectural software. Support parallelism and execution of algorithms on heterogeneous architectures (CPUs, GPUs, FPGAs, etc.).
- **Support the current effort to provide a solid basis for systematic comparisons of experimental results to theoretical predictions.** Test of different approaches, introduce dedicated tools (*e.g.* RIVET) for the comparison and physical interpretation of heavy-ion collisions data, the determination of hadron structure, etc.
- **Call for more long-term storage solutions for gauge ensembles for lattice QCD** Relevant and timely with the advent of exascale facilities.
- **Facilitate and strengthen access for nuclear physics researchers to large HPC centres.** Growing computing needs for both theory and experiment. Allocate funding for enhanced GPU clusters (in particular for AI and ML) within established HPC centres across Europe.
- **Support virtual access infrastructures.** Disseminate theoretical results for the community at large. Capitalize on and further develop initiatives from the EURO-LABS or STRONG-2020 projects.

Machine learning (ML) and artificial intelligence (AI) in nuclear physics

- **Transform ML prototypes into applications for production.** Advance from current proof-of-concept ML projects towards practical applications usable in nuclear physics projects.
- **Train scientific foundation models.** Invest in training and fine-tuning of models tailored for scientific purposes, such as GPT models specialized for nuclear science.
- **Develop research into explainable AI.** Enhance transparency and interpretability in scientific AI applications in nuclear physics and adjacent fields.

Quantum computing (QC) in nuclear physics

- **Formulate a strategy for the quantum-classical interface.** Develop common open-source libraries for integration of classic and quantum software frameworks.
- **Facilitate access to quantum platforms.** Ensure access to state-of-the-art quantum platforms by bridging the gap between academic institutions and private companies, and forming agreements with national HPC centres.
- **Establish a European network on quantum activities related to nuclear physics.** Foster cooperation and knowledge exchange among researchers from different institutions and countries, allowing *e.g.* student exchanges and joint fellowships.

Open Science and Data

Open science and Findable, Accessible, Interoperable, Reusable (FAIR) data offer an important opportunity for the nuclear physics community to uphold the highest research standards and enhance its societal impact, by treating the scientific production process as a strategic asset. The nuclear physics community should vigorously endorse and adopt open science practices, be actively involved in shaping the necessary policies, and lead the way in their implementation. The results of the ESCAPE and OSCARS EU projects should be fully deployed by and for the nuclear physics community.

The richness and diversity of the community present major challenges in applying common FAIR data principles across the variety of data (theoretical, experimental, software, and scientific publication) and research ecosystems (small to large experiments, short to long live collaborations, multi-site travelling detector facilities). To reach this goal of establishing a scalable standard widely adopted by the community, a substantial investment in resources for its implementation and training of the next generation of data specialists is essential.

Progress in fundamental nuclear physics research, which encompasses nuclear structure, dynamics, and nuclear astrophysics, relies on the availability of quality-assured nuclear data characterizing basic nuclear structure and reaction properties. Additionally, advancements in nuclear technologies and their various applications are greatly influenced by the prompt integration of cutting-edge scientific knowledge into these databases. To achieve both objectives, it is essential to recognize that the expertise, research facilities, and best practices required for nuclear data development extend beyond the capabilities of any single field or application. Therefore, a coordinated and collaborative effort at both the national and international levels accompanied by significant investment is imperative.

- The creation and adoption of open science policies and guidelines addressing the pillars of open science such as open data, open source software, and open hardware, as well as promoting best practices within individual institutes and research infrastructures should be strongly encouraged.

- It is strongly encouraged that open access publishing, strategies and infrastructure for data and software publication, and training of researchers in open science practices are pursued.
- Strongly support the application of the FAIR principles and common scientific computing frameworks: encourage training and investment in human resources for data management (data officers, data curators,…) at the various levels (institutions, labs, collaborations) to effectively advance the open data practices.

- The creation of coordination bodies to pursue standardization of the Data Life Cycle to ensure data FAIRness should be supported. The development of guidelines and tools for researchers and collaborations should be engaged towards an effective implementation of these practices.

The primordial role of software in the reproducibility of scientific results should be formalized through systematic software publications and software and computing sessions in workshops and conferences. Software collaborations should be encouraged to improve structuration, and oversight, and enable institutional recognition through awards and career advancement.

Infrastructures for an effective open science

A strong investment in federated infrastructures should be pursued. Relying on technology standards being promoted in other disciplines for data cataloguing and data management, data access, data preservation, user analysis and reproducibility. The various stakeholders (researchers, collaborations, research infrastructures, institutes) should actively contribute to joint activities with the scientific community and follow the technical developments in the field. The implication of the nuclear physics community in existing cross-domain European initiatives should be strengthened and future activities within Joint ECFA-NuPECC-APPEC (JENA) activities should be initiated to implement scalable infrastructures, favour economies of scale, and adapt to the nuclear physics community-specific and diverse needs.

- Combine forces of the European nuclear physics research and applications communities to establish a comprehensive European nuclear data program with well-defined priorities defined by stakeholders and sustainable funding to fulfil the needs in nuclear structure and dynamics, astrophysics and applications.
- Support dedicated efforts to train the next generation of nuclear data experts in data evaluation and the use of AI/ML methods and modern data-driven technologies.
- Strengthen the cooperation between nuclear data curators, data scientists, database programmers and AI/ML experts, and international organizations (IAEA, OECD/NEA).

Nuclear Science - People and Society

It is recommended that European funding bodies and institutions must see nuclear science as a critical societal investment to: inspire the public about nuclear science and its impacts; educate and train the next generation of nuclear scientists; and support equitable career progression with an inclusive approach to diversity across academic, industrial, and vocational career paths.

- **Outreach**: We recommend that funding agencies, national and international bodies, and the community of European nuclear physicists should emphasise the critical societal investment it is to inspire the public about nuclear science and its impacts, facilitated through:

    - establishing and equipping of a European network for outreach, resourced by national and transnational funding schemes, through research-linked and earmarked funding for outreach; and

    - strengthening the provision and support of digital outreach projects and their link to inspiring face-to-face and extracurricular activities.

● **Education**: We recommend that national educational accreditation bodies, funding agencies, universities and educational institutions, in collaboration with the community of European nuclear physicists work to embed nuclear science across all levels of education, highlighting its interdisciplinary nature and impact. This will require:

- the development and resourcing of a European network of science educators across nuclear sciences, to showcase the possibilities of the field, based on the latest teaching methodologies and guided by research; and

- resourcing of the development of research-informed and curriculum-linked training and teaching resources for science teachers, funded by dedicated national and transnational funding.

● **Training**: We recommend that the community of European nuclear physicists in collaboration with funding bodies and other stakeholders resource and support the training of new generations of nuclear scientists, to provide the broad skills base required across experimental and theoretical nuclear physics research, as well as all disciplines and industries in our society, commonly relying on expertise, techniques and skills from the nuclear sciences. This includes the provision of training for technical and engineering staff as well as interdisciplinary researchers.

It is further recommended to create new opportunities for increased international mobility and short-term exchange of early-career and technical personnel across institutions to enhance knowledge exchange and skills transfer.

● **Diversity**: The Nuclear Physics community supports respectful, inclusive and safe work and training environments in academic, industrial, and vocational nuclear science careers.

- We recommend that the network of research organisations, funding agencies, as well as scientific collaborations and conference committees should sign up to and promote a diversity charter, such as the one prepared by NuPECC together with APPEC and ECFA.

- The nuclear physics community and stakeholders should further identify a body in Europe that takes charge of collating and providing an overview of the monitoring of diversity across Nuclear Science in Europe. This information should then underpin recommendations and policies adapted to the nuclear physics community.

● **Careers**: We recommend that equitable and inclusive career development is further prioritised by stakeholders across the European nuclear physics community, giving recognition and visibility to the critical contributions of early career researchers, as the future of nuclear physics and its impact on society. This includes efforts to:

- support tenure track programs giving highly qualified early career researchers (ECR) the opportunity to lead their own group and establish scientific independence (e.g. permanent staff position openings for ECR, ERC Starting Grants);

- provide opportunities for participation in national and transnational training workshops for early career researchers, opportunities to contribute to prestigious committees, and support attendance at highly visible conferences, including through further early career awards; as well as to establish career centres for early career researchers at universities, institutes, and research infrastructures to offer support and training in career development.