Assessment of Implementation of the NuPECC Long Range Plan 2017

February 2022


Note: The NuPECC 2017 Long Range Plan recommendations are marked in green.

1. Hadronic Physics
2. Strongly Interacting Matter
3. Nuclear Structure and Reaction Dynamics
4. Nuclear Astrophysics
5. Symmetries and Fundamental Interactions
6. Applications and Societal Benefits
7. Infrastructures
8. Theory

Preamble

The present NuPECC report is dedicated to the assessment of implementation of the NuPECC Long Range Plan (LRP) from its official presentation in the end of 2017 up to the end of 2021. The goal of the report is to assess in a short text the implementation of the main recommendations of the 2017 LRP in Europe.

The NuPECC liaisons were in charge of the preparation of the short reports for each topic. The reports were prepared in collaboration with the experts of different domains of nuclear physics defined in the 2017 LRP and compiled by the NuPECC Management Group. Each chapter lists the main recommendations of the 2017 LRP and a description of the current status or actions that have been carried out since the LRP was launched.

The assessment will serve as a basis for a timely launch of the next LRP in the coming few years.
1. Hadronic Physics

Completion of the PANDA experiment at FAIR without further delays.

The strategic importance of PANDA for hadron physics cannot be underestimated. It provides a unique opportunity for a comprehensive research programme in hadron spectroscopy, hadron structure and hadronic interactions. The combination of PANDA’s discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world. Despite the delays in its construction, PANDA continues to be viewed as a major flagship experiment, which attracts a large international community. One of the key features of PANDA and the entire FAIR accelerator complex is the availability of an antiproton beam. Therefore, the completion and continued operation of the High Energy Storage Ring (HESR) is vital to sustain this unique research environment.

The time schedule for the setup of PANDA is defined by the construction of the HESR hall. Unfortunately, due to political funding problems, a tender has not yet gone out for its construction. FAIR funding for infrastructure is still missing from Russia and India. Earliest access will not be before 2024. The PANDA collaboration aims to have a Phase 1 version of the detector ready whenever there is beam available. Major parts of the magnets are under construction or have already been produced, such as the yoke of the superconducting solenoid.

![Yoke of PANDA main magnet](image)

As far as the electromagnetic calorimeter is concerned, progress for the forward and backward endcaps is good. The backward endcap will be used in the Phase 0 program in the A1 collaboration at MAMI (Univ. Mainz) for the measurement of $\pi^0$ electroproduction. For the forward endcap all hardware is available and calibration of these parts are foreseen in COSY beams with $\pi^0$ and $\eta$ mesons in 2023.

The status of the Barrel calorimeter is more problematic. Up to now, two slices have been produced, but the order for the rest of the crystals has not been signed due to funding problems. Procurement of the crystals is critical because worldwide there is very limited production capacity for such crystals. The FAIR management is working with high priority on solutions for this problem. As a work-around for the Phase 1 program in charmonium physics, which is one of the major research goals, muon detection was discussed. A contract with Dubna has been signed for the muon detectors of PANDA. However, using only muons would double the necessary beam time to achieve comparable statistical quality.

The internal cluster target was successfully tested last year in the COSY accelerator. The combination of the beam cooling and the target showed that the accelerator and target work together better than expected. The cooling force was sufficient to counteract the beam-target interaction.

A MoU has been signed with the HADES collaboration in the Phase 0 program allowing PANDA members to participate in HADES experiments and permitting the use of the PANDA straw chambers in the upgraded HADES forward detection system for the study of...
electromagnetic properties of hyperons. This experiment has already been accepted and is scheduled for February 2022.

In short, there is significant progress in the construction of several components of PANDA, but there are remaining issues with others. PANDA collaborators are to be commended in being pro-active in using already completed PANDA subsystems in HADES experiments, thereby maintaining momentum in the overall programme.

Support for a research programme in precision physics at existing facilities

The currently operating facilities offer high-quality research programmes. Very significant new results can be expected not only from the big laboratories, such as CERN (LHC, COMPASS), GSI (HADES), JLab, IHEP and NICA, but also from smaller scale facilities, such as DAΦNE, ELSA, MAMI and, in the near future, MESA, where high-precision experiments can be performed. They will not only greatly advance our knowledge about hadrons and their underlying structures, but also explore the limits of the Standard Model. A quantitative understanding of hadronic effects with sufficient precision is necessary to detect signatures for physics beyond the SM. These facilities, whose scientific potential is complementary to FAIR, provide an ideal training environment for future generations of scientists and a highly qualified workforce.

The two main new projects under construction, the NICA facility (Nuclotron based Ion Colliding fAcility) at JINR, Dubna and the MESA facility at Univ. Mainz are well under way.

NICA will be a multi-purpose facility for heavy-ion physics, hadron physics, and includes a component for applied research. Details on the accelerator complex are given in chapter 7 on Infrastructures. The construction of the buildings is almost completed. The first beam circulation in the NICA complex booster was demonstrated in 2020 as well as heavy ion beam extraction and beam transport from the booster to the Nuclotron. The BM@N fixed-target experiment using Nuclotron beams will have its first physics run in 2022 in its almost complete detector configuration. The heavy-ion MPD detector construction is on track to be ready, in its first stage configuration, for the first physics run expected next year. In the field of hadron physics major contributions are expected from the Spin Physics Detector (SPD) collaboration in view of the gluon content of protons and deuterons. First operation of this experiment is planned for 2027.

MESA (Mainz Energy Recovering Superconducting Accelerator) is under construction at the University of Mainz (see article in NPNI 31 (2021)). This experiment aims at electron scattering at modest energies (105 - 155 MeV) but large intensities of 1 mA (upgradable to 10 mA) in energy recovery mode. The civil construction of the MESA experimental hall is close to finalization. The main components for the experimental setups (MAGIX magnetic spectrometers e.g. for measurements of proton radius, P2 parity violating electron scattering, and DarkMESA beam-dump experiment for search of dark matter) have been ordered and are under construction at external companies.

A large program for hadron (baryon) spectroscopy in the sector of light quarks has been performed and is ongoing at the electron accelerators MAMI in Mainz and ELSA in Bonn. These are the Crystal Ball/TAPS experiment at MAMI, the Crystal Barrel/TAPS experiment at ELSA, and the BGOOD experiment at ELSA. The main aim of these experiments is to get a much better data base for the excited states of the nucleon. The problem is, that the states with light quarks are very broad and strongly mixed. Improvement can be only achieved if the data bases not only for differential cross sections but also for a reasonable set of polarization observables become available so that partial wave analyses can be constrained much more. Both the CBall/TAPS experiment and the CBarrel/TAPS experiment have therefore explored measurements with polarized, tagged photon beams (linearly and circularly) and polarized hydrogen and deuterium targets (actually polarized butanol and polarized deuterated butanol). In particular, for the polarized targets, there was a very fruitful collaboration between Mainz, Bonn, and Dubna. For the last four years only one of these targets was operational, which has been used in both labs. Currently, a second target is being commissioned so that in future double polarization measurements in both labs will be possible in parallel. Results from these experimental programs have already made a significant impact on the interpretation of hadron
structure. Actually, almost all new entries in the Review of Particle Data tables for baryons with light quarks come from these experiments and the similar Jlab CLAS experiment.

The Bonn BGOOD experiment is somewhat complementary. It uses an electromagnetic calorimeter covering almost $4\pi$ covering, no polarized target but a high-resolution magnetic dipole spectrometer at forward angles. This arrangement makes it especially sensitive to reactions with fast forward going particles and large energy deposition in the central detector, which allows for better studies of hadronic interactions.

At MAMI the program centred around electron scattering experiments with the three magnetic spectrometers of the A1-collaboration was also successfully continued. Major data taking campaigns have been carried out for the measurement of transversal asymmetries of nuclei which serve as important input for a future neutron skin program at MESA, and high-precision measurements of the polarizability of the proton at A2. A new experiment to measure the electric form factor of the proton is currently prepared in A2 in cooperation with St. Petersburg/Russia and other international partners. The detector will consist of a high-pressure time projection chamber as an active proton target allowing detection of the recoil protons; a novel approach for the determination of the momentum transfer with reduced systematic uncertainties.

In this context the MUSE experiment at the Paul Scherrer Institute (PSI) in Villingen, Switzerland should also be mentioned, which has just started the first data taking campaigns. It aims at a detailed comparison of electron and muon scattering (both charge states) off the proton in view of the proton radius problem.

Also, in the last few years the COMPASS experiment at CERN has significantly contributed to hadron structure and spectroscopy with light quarks. In 2022, it will have its last data-taking campaign. After the completion of the COMPASS program, the AMBER Collaboration will start a new generation of experiments at the CERN SPS, with the goal of investigating the emergence of hadron mass. This new project, approved by the CERN Research Board in December 2020, will allow for a great variety of measurements addressing fundamental issues of strong interactions.

The LHCb experiment at CERN, which was originally mainly designed for the study of $CP$ violation, has also contributed much to hadron spectroscopy in a somewhat different field, namely the investigation of hadrons with heavy quarks. This kind of spectroscopy (also planned for PANDA) opens a new window because the states with heavy quarks are much narrower than those with light quarks and can therefore be much better separated. In addition, states with two heavy quarks, like the proposed $\Xi^{++}_{cc}(ccu)$ have a very different structure from baryons with light quarks, resembling more a double-star system with a light planet, allowing to test the strong interaction in a different environment. There were even suggestions for a pentaquark of the $(c\bar{c}uudd)$ type. Results for such states with heavy quarks or even exotic ones have also been reported from other colliders like BESIII (European contributions e.g. from Italy) and BELLE. Following the recommendations of the NuPECC 2017 LRP, the DAΦNE $e^+e^-$ collider in Frascati has also been providing beam time for nuclear physics experiments. In particular, SIDDHARTA-2 is currently running and has received adequate support through national and international funds. DAΦNE has provided beam to the experiment during the first half of 2021 and is scheduled to run for the whole of 2022 to complete the data taking.

Contribution to non-European experiments has continued in particular for Jlab, Newport News, USA. The funding for personnel was stable since the number of researchers from EU and UK has been roughly constant in the period 2016-2021. The funding for equipment has been sizeable up until the completion of the upgrade of the experimental halls (2018). Italy invested 10 M€ in Jlab12 (CLAS12+Hall A), but there are no other big investments planned for the future. UK investment was 3 M€ in the upgrade (CLAS12+Hall A) for a similar period. There is some EU investment in the hardware for future experiments (ALERT, NPS, MOLLER), but less sizeable. However, in this instance the NuPECC recommendation has been implemented. The BESIII experiment (BEijing Spectrometer) mentioned above has been taking data since 2009 and will continue at least until 2030. It is fully supported by IHEP and national funding agencies such as the Italian INFN, in accordance with NuPECC recommendations to support...
precision physics programs at existing facilities. In total, about 32 fb$^{-1}$ of data have been collected in 12 years, covering an extensive physics program including hadron form factors, R-values and QCD, light hadron spectroscopy, gluonic and exotic states, physics with $\tau$ -leptons, XYZ particles, charm mesons, and charm baryons. A further upgrade of the BEPCII accelerator and spectrometer is planned for 2024, with an optimized beam of 2.35 GeV and three times higher luminosity, and with the installation of the CGEM Inner Tracker proposed by the Italian collaboration to BESIII and supported by a European, IHEP and INFN network.

Support for theory and computing

Many of the major insights of recent years have been gained by confronting increasingly sophisticated theoretical tools with experimental data. The interplay between complementary theoretical approaches such as lattice QCD, effective field theories and functional methods has been a great asset for obtaining a deep understanding of hadronic properties in terms of fundamental interactions. Further progress depends crucially on the availability of large-scale computing facilities. We recommend that European computing laboratories receive the support that is necessary to provide an environment for internationally competitive calculations in lattice QCD.

Since the publication of the LRP 2017, major new results in theoretical hadron physics have appeared that relied crucially on the availability of large-scale high-performance computing resources. Examples include results on nucleon structure observables, hadronic contributions to the muon anomalous magnetic moment, as well as many new results on hadron resonances and scattering. Many member states have upgraded their national computing centres and started new initiatives (e.g. NHR and NFDI in Germany) promoting high-performance computing, data infrastructure and artificial intelligence, all to the benefit of the research effort in theoretical hadron physics and lattice QCD. On the European level, the EuroHPC Joint Undertaking is a new initiative designed to establish a pan-European approach to supercomputing, with plans to deploy several multi-petascale and two exascale machines by 2023. An effort has been started to establish specific access modes which would grant additional resources for the European lattice QCD community. Further preparations have been delayed due to the Covid-19 pandemic but will be resumed.
2. Strongly Interacting Matter

Experimental programme

Vigorous efforts should be devoted to the continuation of the heavy-ion program at the LHC with Runs 3 and 4, including manpower support and completing the planned detector upgrades.

During the Long Shutdown 2 (LS2) of the Large Hadron Collider (LHC), all LHC experiments have made major upgrades of their detectors and readout systems, which will enable the full exploitation of the LHC heavy-ion beams in Run 3 and 4.

In the context of the European Strategy for Particle Physics process, the expression of interest for a next-generation heavy-ion experiment at the LHC beyond the current plans for Run 3 and 4 was presented.

At intermediate energies, we recommend the continuation of the on-going programs: HADES at SIS-18, NA61 at the SPS.

Since 2017, both experiments have continued their data taking campaigns and physics analyses. Limitations come only from the restricted availability of beams at GSI (during the preparations for FAIR) and at CERN (during the 2019-2021 shutdown).

In order to investigate nuclear matter at high baryonic density, the timely construction of SIS-100 at FAIR and the realization of the CBM experiment are of utmost importance.

With the newly established timeline for the FAIR project the construction of the CBM experiment is progressing well and the aim is to be ready for beam by the end of 2025. All major components have been designed and tested under realistic conditions in the mini-CBM experiment at SIS18, which will be also used as a demonstrator for the ambitious software selection concept that CBM is pursuing to make optimal use of its high bandwidth data acquisition backbone.

In parallel, efforts should continue in order to support developments for a future SIS-300 upgrade. FAIR does not yet have a detailed plan for SIS-300, various options are being considered.

We recommend the completion of the BM@N experiment at JINR, and the construction of the NICA facility and the realization of the associated MPD experiment.

About 80% of the construction work based on the design configuration of the NICA complex has been completed. The buildings will be ready for installation of accelerator components in early 2022. Construction of the key components of the accelerator is progressing well, despite of COVID-19 restrictions. On December 30, 2020 the commissioning of the new Booster synchrotron took place successfully. First fully exclusive measurements in inverse kinematics experiment on short-range correlations at BM@N started in 2018 with a 4 AGeV $^{12}$C beam. Analysis of the collected data were published in 2021 in Nature Physics 17, 693 (2021).

The Hybrid Central Tracker for heavy ion runs in 2022 (7 GEM full planes + 3 forward Si planes) is under construction. For the physics run with Xe beam in spring 2022 (800 hours of physics data taking), at the Booster – Nuclotron accelerator system, the plan is to collect $2\cdot10^9$ Xe + CsI interactions.

The construction of the MPD detector for studies of dense baryonic matter in heavy ion collisions is progressing rapidly and the first heavy-ion run with the MPD is foreseen in 2023.

Exploratory studies on prospective future heavy ion projects, namely AFTER@LHC, NA60+ at the SPS, and a heavy-ion program at the Future Circular Collider, should be continued.

AFTER@LHC is a study group supporting the effort towards a full physics program using the proton and ion LHC beams in the fixed-target modes. The multi-TeV energy of the LHC beams will allow for the most energetic fixed-target experiments ever performed. LHCb is already progressing towards this goal.
The NA60+ project is proposing an experiment at the CERN SPS, devoted to the study of hard and electromagnetic processes in Pb-Pb and p-A collisions, with an energy scan in the range $5<\sqrt{s}<17$ GeV. An Expression of Interest was submitted in 2019, while a Letter of Intent is in preparation and will be submitted in the first months of 2022. The experiment aims at taking data after LHC Long Shutdown 3.

**FCC – Future Circular Collider**

A sub-group of the FCC physics program was established focusing on studies with heavy ions (conveners: Nestor Armesto, Andrea Daïnese, Silvia Masciocchi, Carlos Salgado, Urs Wiedemann). It produced the Yellow report: *Heavy ions at the Future Circular Collider* ([https://arxiv.org/abs/1605.01389](https://arxiv.org/abs/1605.01389)). An example of recent physics studies by operating FCC with Pb–Pb and p–Pb collisions at $\sqrt{s_{NN}} = 39$ and 63 TeV, respectively, per nucleon–nucleon collision, with projected per-month integrated luminosities of up to 110 nb$^{-1}$ and 29 pb$^{-1}$, respectively, can be found in the following paper: ([https://arxiv.org/pdf/1901.10952.pdf](https://arxiv.org/pdf/1901.10952.pdf)).

**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 in its more ab initio works (quantum chromodynamics)

The support for theory (including both the modelling of heavy ion collisions, and more ab-initio approaches like lattice QCD) has remained roughly constant since the report was drafted, i.e., throughout the period 2017-2020. During this period, six ERC grants were attributed to projects in this area. Within fluctuations, this number seems on par with the corresponding numbers prior to 2017. Although it is hard to draw definitive conclusions from these small numbers, they seem to suggest that

1. the theory community in this area has been continuously active in setting up new ideas and proposals and
2. a reasonable number of these proposals have been judged to be of high interest at the European scale.

A close collaboration between theorists and experimentalists should be encouraged and nurtured, since most progress in heavy ion physics stems from a continuous exchange between them

The current situation is conjecturally in a low moment because of the COVID-19 pandemic that has frozen all in-person interactions (like conferences, where many ideas are exchanged) for a good part of the past two years. People who already had collaborations have managed to continue them remotely, but this has definitely been an impediment for starting new ones. It seems however that, judging by the number of conference projects for 2022 that the situation is progressively getting back to normal.

ECT* continuously plays a key role in promoting synergistic contacts between experimentalists and theorists in the field of Strongly Interacting Matter.

In Jyväskylä, a new Centre of Excellence in Quark Matter was established. It is led by Tuomas Lappi and includes groups working on QCD theory and experimentally at ALICE.

Several work packages of the EU Project STRONG-2020 ‘The strong interaction at the frontier of knowledge: fundamental research and applications’ (funded in Horizon 2020 research and innovation programme under grant agreement No 824093) are very effective examples of close collaboration between experimentalists and theorists.

**Miscellaneous**

Computing: resources should be secured to face the increasing needs in computing power and data storage, both by theory and by experiments. In parallel, one should invest in developments of new technology and new algorithmic paradigms to fully exploit novel computing architectures

Computing resources for the ongoing and upgraded experiments could be secured, mainly at the host labs or within the Worldwide LHC Computing Grid (WLCG) for LHC in preparation for Run 3. This is based on a yearly increase of the computing resources by +15-20% at a constant budget.

Theoretical work is benefiting from the continuous development of HPC systems in Europe, where the nuclear physics community was successful with its project proposals. Access to these resources has
been simplified through various EU-programs, e.g. the ESCAPE (https://projectescape.eu) cluster within European Open Science Cloud (EOSC).

Use of Graphical Processing Units (GPUs) has become more common, mainly in the online computing sections of the experiments and in theory calculations. Non-x86 processor architectures are becoming an interesting alternative which is actively explored. The portable programming of these new technologies remains however a challenge and continuous support for software development is needed, e.g. for the common and multi-lab experiment frameworks like FairRoot. An interesting opportunity for the future opens up with the increased capabilities and general availability of quantum computers, prototype theory calculations have shown the future potential.

Machine learning algorithms are routinely used for pattern recognition, in quality assurance, detector control and physics analysis. Their use in hybrid-models has significantly reduced computing needs for some simulations. Algorithms and software frameworks have been adapted to the now-common multi-core architectures, which required changes to the programming and data model.

In view of future experiments, characterized by very high particle densities, one should continue at all times R&D of detectors employing new techniques to reach faster signal production and collection, to handle higher data rates, and to stand higher radiation levels.

Following the documents of 2020 EPPSU (https://europeanstrategyupdate.web.cern.ch/) the Detector R&D Roadmap process was launched by ECFA in 2021 with the aim of balancing the global efforts for detector R&D in Europe, taking into account progress with emerging technologies in adjacent fields. After an extensive consultation phase the ECFA Detector Roadmap Panel prepared the main conclusions and recommendations and the final roadmap was approved by Plenary ECFA in November 2021 and presented to CERN Council in December. Detector R&D needs for ALICE, FCC with heavy ions, and FAIR experiments were included. The document can be downloaded via this link: https://cds.cern.ch/record/2784893

Various initiatives in the framework of the Joint ECFA-NuPECC-APPEC Activities (JENAA) Expression of Interest “Synergies between the Electron-Ion Collider and the Large Hadron Collider experiments” are underway for fostering the collaboration between European and American researchers in the field of detector R&D of shared interest for the experimental programs at EIC and the LHC.
3. Nuclear Structure and Reaction Dynamics

Full support to existing stable beam facilities offering transnational access in the ENSAR2 H2020 project (GANIL, GSI, LNL-LNS, ALTO, JYFL, KVI-CART, CERN-ISOLDE, NLC, and IFIN-HH). In particular, the very high-intensity stable-ion beams from LINAG (of SPIRAL2), the super-conducting cw-linac under construction at GSI, and the SHE factory at Dubna offer exciting opportunities particularly for superheavy research.

ENSAR2 H2020 project

The core aim of the Integrating Activity ENSAR2 project (https://www.ensar2.eu) from 2016 to August 2021 was to provide TransNational Access (TNA) to the major European facilities GANIL, GSI, LNL-LNS, ALTO, JYFL, KVI-CART, CERN-ISOLDE, NLC, and IFIN-HH. TNA has been vital for the success and achievements of the facilities. The project strengthened the collaboration between the complementary research facilities and optimized their utilization to address common scientific goals. TNA was essential to maintain strong and diverse research programs at universities and research institutions across Europe that are fully aligned with the scientific goals set out in the LRP. The Facility Coordination Group (FCG) of ENSAR2, comprising the directors of the infrastructures and the chairpersons of their programme advisory committees, worked furthermore on the harmonization of scientific policies. ENSAR2 signed memoranda of understanding with facilities outside Europe: IMP-CAS Lanzhou (China); TIFR Mumbai (India); CNS Tokyo, KEK Tsukuba, RCNP Osaka, RNC RIKEN Tokyo (Japan); JINR Dubna (Russia); iThemba Cape Town (South Africa); ANL Argonne, NSCL East Lansing (USA). Based on these MoU, international researchers from outside Europe could receive support at ENSAR2 facilities, while European researchers were reciprocally supported at international facilities. This widened opportunities for European researchers and enabled them to use the most suitable facilities worldwide. Several international collaborations involved moving equipment such as detectors from Europe to international facilities and vice versa, taking advantage of their complementarity. The FCG proposes moving from case-by-case cooperation to a harmonized TNA scheme including international facilities outside Europe. ENSAR2 fulfilled its obligations concerning TNA. As a follow-up, a new Horizon Europe proposal, EURO-LABS (https://indico.ph.tum.de/event/6861/contributions/4572/attachments/3713/4611/EURO-LABS_NuPECC.pdf), was submitted to the EU and was accepted for funding in January 2022.

GANIL/SPRAL2 – LINAG

The GANIL cyclotrons operated for about four months per year in the period 2016 – 2021, delivering both stable and radioactive beams (produced in flight at the LISE separator and ISOL beams from SPIRAL1), leaving time for construction and commissioning of the SPIRAL2 facility. The AGATA campaign at GANIL from 2014 to 2021 is considered a highlight in the program on nuclear structure and reactions. The performance of AGATA, which was coupled to the VAMOS++ magnetic spectrometer, the MUGAST charged particle array, PARIS scintillator array, NEDA neutron detector and other ancillary detectors, opened new avenues in high-resolution γ-ray spectroscopy. Experiments addressed, among other topics, the evolution of the shell structure in exotic nuclei, nuclear deformation, cluster states, the role of three-body forces, and reactions relevant for stellar nucleosynthesis. Other major detectors used recently at GANIL are the INDRA-FAZIA charged particle array, the ACTAR-TPC active target, and the Particle-Identification Silicon-Telescope Array (PISTA). The linear accelerator of SPIRAL2 (LINAG) was completed and commissioned in the period 2015 - 2019 and it has been delivering science from 2021 with proton and deuteron beams of nominal energies and intensities as well as a high-flux of fast neutrons. Full commissioning of heavy-ion beams is foreseen in 2022. In 2021, a second heavy-ion injector with a maximum A/q of 7 (NewGAIN project) was funded via a French EQUIPEX grant. The injector will largely increase the intensities for heavy-ions with A ≥ 40 and will enter into operation by 2027. The LINAG serves three experimental areas: Neutrons for Science (NFS), which began experiments in 2021, Super Separator-Spectrometer (S$^3$), which is presently in the final construction phase and is expected to start experiments in 2024, and DESIR (Experimental Hall for experiments with low-energy RIB from S$^3$ and SPIRAL2), which is in its final design and integration phase and envisages early science operation by 2027. The progress of the construction of the SPIRAL2 facility is reviewed in the chapter 7 of this document.
GSI-cw linac

To keep the SHE program at GSI competitive on a high level, a standalone superconducting linac HELIAC (HElmholtz LInear ACcelerator), a common project of GSI and Helmholtz Institute Mainz (HIM), was developed. In 2017 the first section of the linac was successfully commissioned and extensively tested with beam at GSI. The HELIAC will be used to accelerate ions with a mass-to-charge ratio up to A/Q = 6 from the input energy of 1.4 MeV/u up to an output energy between 3.5 MeV/u and 7.3 MeV/u. Commissioning of the linac with three cryomodules is planned for 2026.

SHE factory

The "Superheavy Element Factory" based on a dedicated new DC280 cyclotron was constructed at JINR Dubna. The main task of the complex is the synthesis of new chemical elements with atomic numbers 119, 120 and higher, as well as a detailed study of the nuclear and chemical properties of known superheavy elements. In the first experiments carried out in 2020-21, many tens of new events for isotopes of the superheavy elements Z=114 (flerovium) and Z=115 (moscovium) have been detected. A new gas-filled recoil separator, DGFRS-3, for detailed spectroscopic studies of heavy isotopes is being developed and will be installed at the DC280 cyclotron. High beam intensities from the DC280 cyclotron and the increased detection efficiency of the modernized GABRIELA setup for gamma rays and conversion electrons will allow new spectroscopy experiments in 2022 aimed at studying the nuclear structure of superheavy nuclei in the complete fusion reaction $^{48}$Ca+$^{243}$Am→$^{291}$Mc*. The SHE factory in Dubna is an integral part of the international research program on super-heavy elements complementing the facilities at GSI in Germany, RIKEN in Japan, LBNL in the USA, and GANIL/SPIRAL2 in France. Experimental activities at the SHE factory are eligible for transnational access support in the framework of the EURO-LABS project.

EURISOL is the long-term goal that will ensure unique physics opportunities. In the meantime, it is important that the full aims of the major facilities (SPIRAL2, HIE-ISOLDE and SPES) in the framework of the EURISOL-DF are realised as soon as possible.

The ISOL facilities operating in Europe are running very successful programs that contribute significantly to the scientific goals described in the long-range plan, while those under construction have made good progress. The ISOLDE facility at CERN offers the widest range of reaccelerated ISOL beams in the world covering almost the entire nuclear chart. The construction of the new superconducting post-accelerator increased the beam energy from 3 to 10 MeV per nucleon, widening the scope of the facility significantly. New instrumentation such as the ISOLDE Solenoid Spectrometer (ISS) further expanded the scientific program, and new projects such as a compact storage ring or a trap for studying the interaction between antiprotons and exotic nuclei are being pursued.

The first phase of the SPIRAL2 facility has been partially completed, with the LINAG fully commissioned and the Neutrons for Science facility in operation. The remaining parts of the first phase, i.e. the Super Separator-Spectrometer (S³) and the low-energy project DESIR, are under construction and expected to be operational in 2024 and 2027, respectively. The decision on the construction of phase 2 of SPIRAL2, i.e. the production of high-intensity ISOL beams, was postponed by French funding agencies in 2015.

The SPES project at Legnaro is in an advanced construction stage, with the new cyclotron and the target-ion source already installed and the first ISOL beams expected in 2023. The operation of the AGATA spectrometer at the SPES facility opens unique opportunities for nuclear structure and reactions studies.

With ISOL@MYRRHA, a new ISOL facility is under construction in Belgium. The smaller facilities IGISOL at Jyväskylä and ALTO at Orsay with their successful complementary programs complement the range of ISOL beam facilities in Europe. There is generally a good collaboration between the various facilities, both scientifically and in technical developments. It was planned that the EURISOL Distributed Facility (EURISOL-DF) would enhance complementarities and avoid duplication of efforts in the RIB developments at ISOL facilities in Europe. It would also largely enhance competitiveness of the European nuclear science and its applications at the global level. In the period 2016-2020 the EURISOL MoU Steering Committee initiated and coordinated in close collaboration with the EURISOL User Executive Committee an intensive preparatory work for EURISOL-DF to be proposed as distributed facility for the 2021 ESFRI roadmap. Dedicated Steering Committee and working group meetings, conferences, and meetings with concerned funding agencies and infrastructures were
organized. Technical R&D work was pursued in the framework of a Joint Research Activity of the ENSAR2 H2020 project from 2016 to 2021. However, because two major partners (IN2P3 France and CERN) did not agree to support the project, the EURISOL-DF project was closed by the EURISOL Steering Committee in January 2020. At present it is considered to organize cooperation within a league of European RIB facilities.

The development and construction of a large variety of state-of-the-art instrumentation providing optimal exploitation of different types of beams need support. In particular, the gamma detector AGATA is a flagship and it has been used since 2010 at LNL, GSI and GANIL. The timely completion of the full AGATA spectrometer and the provision of adequate support and maintenance is of highest importance to address the exciting science programme at both the stable and radioactive beam facilities.

AGATA is a collaborative European project to construct and operate a gamma-ray tracking spectrometer based on segmented Ge detectors with an unparalleled level of detection sensitivity. AGATA concluded its successful 7-year campaign at GANIL in 2021 and is now being installed at Legnaro, where an initial campaign with stable beams will be followed by the exploitation of radioactive beams from the new SPES accelerator. The science output from the previous campaigns at Legnaro, GSI, and GANIL is very well aligned with the goals described in the long-range plan. AGATA has so far produced 85 science publications, 108 technical publications, and 105 theses. The recommendations in the 2017 long-range plan were crucial in taking AGATA beyond the milestone of 60 detectors as defined in its memorandum of understanding (MoU) that expired in 2020. The science case for AGATA was internally reviewed (and published in 2020 in European Physical Journal A) in preparation of a new MoU to take the project to 4π coverage with 180 detectors. The science program of AGATA is expected to have an enormous impact on nuclear structure studies at the extremes of isospin, mass, angular momentum, excitation energy and temperature. AGATA is expected to be hosted by all major European nuclear structure facilities (FAIR, GANIL/SPIRAL2, HIE-ISOLDE, JYFL and LNL/SPES). In addition, an international review of the science, technology, organisation, management, and resources of the project was launched and its recommendations were submitted to European funding agencies in 2020. It was recognized that AGATA will be a flagship instrument in Europe for nuclear research with stable and radioactive beams, and its timely completion was recommended. It was noted that the 4π instrument would be particularly powerful for physics with weak radioactive beams furthest from stability, and that an intermediate 3π configuration had unprecedented discovery potential when coupled to magnetic spectrometers and other ancillary detectors. As a result, a new MoU was established in 2021, and already signed by most of partners, covering the continued operation at the host laboratories and a completion of the 3π device in 10 years. This can be considered as a very positive outcome.

We recommend the completion and operation of the unique ELI-NP facility. Its scientific programme with its new and unique probes (high power lasers and brilliant gamma beams used also for an IGISOL set up) needs to be supported.

The general status of the ELI-NP facility is discussed in the infrastructure section of this document (chapter 7). The most relevant part of the facility for studies of nuclear structure and reactions is related to the gamma beam program. After initial delays, the construction of the Variable Energy Gamma System (VEGA) is progressing well and completion is scheduled for 2023. A wide range of detectors, including an array of 34 large-volume LaBr$_3$:Ce and CeBr$_3$ detectors, 37 liquid scintillator detectors for high-energy neutrons, 25 lithium-glass detectors for low-energy neutrons, an array of silicon-strip detectors, and a moderated high-efficiency neutron counter made of $^3$He tubes embedded in polyethylene are available for experiments. Day-one experiments with the ELI-NP gamma-beam system include nuclear resonance fluorescence (NRF) experiments, photo-neutron reaction measurements, studies of $(\gamma,\alpha)$ and $(\gamma,p)$ reaction cross sections, and photo-fission experiments.

The urgent completion of FAIR, with the wide and unique programmes on nuclei far from stability at NUSTAR with the SUPER-FRS and its instrumentation, are of utmost importance for the community. It is also important that the upgraded GSI facility will continue to perform a science programme and instrumentation commissioning during Phase 0 of FAIR.

The NUSTAR collaboration has been continuously developing the detector systems to be used at the Super-FRS facility at FAIR. Major milestones have been achieved, such as the commissioning of the
GLAD dipole magnet for the R3B experiment, the FATIMA LaBr$_3$ detector array for DESPEC, the prototype of the Cryogenic Stopping Cell to deliver very low energy beams to MATS and LASPEC, and new Schottky detectors for ILIMA at the new FAIR collector ring. Several other detector systems have also been tested and used to deliver science at external facilities (ANL, RIBF, JYFL, etc.). Within FAIR phase-0, the first NUSTAR experiments exploiting the new detectors have been performed using the current GSI machines (SIS18 and FRS) and delivered important new scientific results. The construction of the NUSTAR buildings is proceeding as planned, planning of the cave infrastructure is ongoing and the installation process should start in 2024. In the current planning NUSTAR should receive first beam from the Super-FRS in Q4/2025.

Other small and medium scale facilities, often university based, should be supported for their specific programmes, for the development of new instruments and also to provide education and training of the next generation of researchers.

Small and medium scale facilities have played a very important role for nuclear structure and reactions research in Europe and contributed significantly to pursuing the scientific goals described in the LRP. Their importance cannot be underrated in a period when the major facilities GSI, GANIL, and ISOLDE could only offer limited amounts of beam time due to the construction of the FAIR and SPIRAL2 facilities and the long shutdown at CERN, respectively. Several new instruments have been developed and exploited in recent years. Notable examples include the GALILEO gamma-ray spectrometer at Legnaro, the nu-Ball spectrometer and the LICORNE neutron-beam facility at Orsay, and the Jurogam and MARA spectrometers at Jyväskylä. The IGISOL facility at Jyväskylä has been continuously upgraded, making it a competitive and highly complementary radioactive beam facility. Many small-scale accelerator laboratories maintain competitive and often highly specialized research programs, e.g. at NCSR Athens, IFIN-HH Bucharest, ATOMKI Debrecen, IKP Köln, CCB Krakow, OCL Oslo, NPI Rez, HIL Warsaw, and RBI Zagreb. Several of these laboratories contribute to the construction and testing of infrastructure for the large-scale laboratories. The small-scale laboratories play an essential role for the education and training of students and young researchers.

Support is needed for theory focusing on a universal description of nuclear structure to provide bridges between the ab-initio, shell model and EDF methods. Effort should be made to integrate reaction dynamics and nuclear structure so that the input required for reaction calculations is based on state-of-the-art structure calculations. The challenge of interpreting the extraordinary variety of nuclear data requires expansion of the theory community in terms of available manpower and also in available computational resources.

Nuclear structure theory has seen substantial progress over the last few years. New ideas and technical developments have helped to expand the range of ab initio nuclear many-body theory significantly. New approaches such as the method of eigenvector continuation accelerate the convergence of calculations using many-body perturbation theory, providing an efficient and accurate tool to improve many-body expansions independently of the origin of the Hamiltonian. Efforts have also been made to unify the configuration interaction (shell model) and energy density functional approaches, and effective shell model Hamiltonians have been derived for example from the finite-range density-dependent Gogny force. Progress was also made in rooting reaction calculations in nuclear structure theory, for example by deriving ab-initio optical potentials from self-consistent Green’s function theory. It can be expected that machine learning approaches and the rapidly expanding field of quantum computing will provide substantial further advancement for nuclear theory. Human and computational resources in nuclear theory are reviewed in the theory chapter of this document (chapter 8).
4. Nuclear Astrophysics

The preparation of the NuPECC Long Range Plan in 2017 has defined general questions to address for the nuclear astrophysics community:

- What are the nuclear processes that drive the evolution of the stars, galaxies and the universe?
- Where are the building blocks of life created?
- How do nucleosynthesis processes evolve with time?

Since the publication of the LRP the field has seen rapid progress, e.g. through the observation of neutron star mergers as a major site of nucleosynthesis in 2017. The successful observation of gravitational waves from such events together with advances in neutrino observations have impacted on every aspect of the field and led to true multi-messenger astrophysics. These developments will take centre stage in the next LRP, but could not have been foreseen at the time. However, the responses to many of the recommendations made in LRP already reflect these developments. Here we focus on the recommendations made at the time to address these questions.

We strongly support the upgrade of LUNA with a multi-MV accelerator and associated infrastructure, allowing access to a new range of nuclear reactions.

Over the last 4 years, several processes relevant to the CNO, MgAl and NeNa cycles have been studied using the LUNA 400 kV machine, a Singletron accelerator which has been operational since 2001. These studies have contributed to unveil the origin of some meteoric stardust [1] and to shed light on the speed at which the NeNa cycle operates [2, 3]. The cross section of the most important reaction affecting the primordial abundance of deuterium during the Big Bang Nucleosynthesis (BBN), i.e. \( ^2\text{H}(p,\gamma)^3\text{H} \) has been measured with high precision.

More recently, the measurement of the rate of the important stellar neutron source, the \( ^{13}\text{C}(\alpha,n)^{16}\text{O} \) reaction, has been performed directly inside the Gamow peak. The Laboratori Nazionali del Gran Sasso (LNGS) is currently expanding the accelerator laboratory with special funding of the Italian Ministry of Research, by installing a new 3.5 MV Singletron machine designed and built by High Voltage Engineering Europe (HVEE). The 3.5 MV machine will be equipped with two independent beam-lines. Acceptance tests at HVEE proved that the machine can deliver intense proton, helium, and carbon beams (1, 0.5 and 0.15 mA respectively) with well-defined energy resolution and stability. The new accelerator will be installed underground at LNGS in the autumn 2021, with initial scientific exploitation presently foreseen by 2023.

We strongly recommend that dedicated nuclear astrophysics programs at universities and small-scale facilities be supported to enable them to continue and extend their high impact science. We furthermore recommend that access to such facilities is maintained through the transnational access programme.

The new project ChETEC-INFRA Starting Community of Research Infrastructures for nuclear astrophysics (2017-2021, coordinating institution HZDR/DE, [https://www.chetec-infra.eu](https://www.chetec-infra.eu)) aligns with several of the recommendations included in the 2017 LRP. Specifically, ChETEC-INFRA opens up EU-supported transnational access to a number of small-scale facilities (nuclear laboratories, telescopes, and a supercomputer). It includes a task addressing nuclear reaction target developments, for both solid and gas targets. Several established and several new nuclear astrophysics scientific schools are supported by this network along with a new, monthly online school, thus strengthening training of future scientists and coherence in the field. Finally, a dedicated task addresses the interface to funding agencies and to countries that are under-represented in this research field.

After the successful ENSAR2 project which encompassed an ensemble of Networking (NAs), Joint Research (JRAs) and Transnational Access Activities (TAs), to ensure improvement of the access provided by ten infrastructures and the theoretical physics facility: ECT*, the EURO-LABS project (accepted in 2022) supports the activities necessary to the improvement of experimental facilities and/or the successful implementation and interpretation of experiments including those related to nuclear astrophysics.
We strongly support the completion of the FAIR facility, and its exploitation by the four experimental pillars APPA, CBM, NUSTAR and PANDA.

The NUSTAR collaboration has a strong pillar regarding experiments concerning key questions of nuclear astrophysics. Within the NUSTAR Phase 0 program at GSI, using detectors already developed for FAIR, several experiments were successfully performed.

The HISPEC/DESPEC program revolves around the study of nuclear structure in the exotic neutron-rich side of the nuclide chart. The nuclei of mass A≈195 are key to the understanding of nucleosynthesis in the rapid neutron capture process (r-process). Observables such as lifetimes, neutron emission probabilities and decay strengths are examined. Combining detailed spectroscopic information (level schemes and transition probabilities), revealing the details of the underlying nuclear structure, with total absorption gamma-ray spectroscopy, accessing the full beta strength distribution, for the most exotic nuclei in this region reachable at FAIR Phase-0, provides a benchmark for improving the theoretical models and increase their predictive power for the properties of the much more exotic r-process path nuclei.

The ILIMA collaboration studied the beta-lifetime of the first excited state at 2.3 keV in $^{205}$Pb, a key nucleus for s-process nucleosynthesis at A≈205 in spring 2020. The only way to measure the corresponding decay matrix element is to employ the bound-state beta decay of fully-ionized $^{205}$TI. The ESR at GSI is presently the only facility where fully-ionized secondary beams can be stored for extended periods of time. Furthermore, the capability of the ESR to deaccelerate ion beams to energies in the vicinity of the Gamow window of the p-process has been employed to study proton capture reactions. In 2020, the stable beam reaction $^{124}$Xe(p,$\gamma$)$^{125}$Cs was measured in a pilot experiment. In 2021, for the first time, a radioactive $^{118}$Te beam was stored successfully studying the reaction $^{118}$Te(p,$\gamma$)$^{119}$I and addressing this p-nucleus, which is produced in explosive stellar events through disintegration of heavy-seed nuclei. Finally the R3B collaboration studied the Coulomb dissociation of $^{16}$O in order to access the reaction $^{15}$C(t,$\gamma$), which is a key reaction in stellar nucleosynthesis and in stellar model calculations.

We strongly support the full completion of the next generation of radioactive ion beam facilities, including HIE-ISOLDE, SPES-INFN and SPIRAL2. We highly recommend the implementation of phase 3 of HIE-ISOLDE and an upgrade of the GANIL CIME cyclotron, enabling the study of capture reactions of astrophysical importance. The installation of a new storage ring at HIE-ISOLDE is also recommended. In the longer term, we strongly support progress towards EURISOL.

GANIL – SPIRAL 2

GANIL with SPIRAL1-CIME is very well placed for the production and acceleration of light radioactive beams of low and medium energy, which are very well adapted for nuclear astrophysics.

SPIRAL1 radioactive beams were used recently to probe nuclear forces beyond the proton drip line. The unbound proton-rich nuclei $^{16}$F and $^{15}$F were investigated experimentally using the resonant elastic scattering method. It was observed that the strength of the nucleon-nucleon effective interaction is significantly reduced with respect to their mirror nuclei $^{16}$N and $^{15}$C. This asymmetry can be explained entirely by the continuum coupling effect.

An intense radioactive beam of $^{19}$Ne was produced at SPIRAL1 and used to measure its half-life with a real-time digital acquisition system. The resulting half-life is the most precise up to now for $^{19}$Ne. Its value is important to constrain the up-down element of the CKM quark mixing matrix, providing the second most precise value of this parameter.

A radioactive beam of $^{37}$Ca produced by fragmentation reactions at LISE was used to reinvestigate the $^{35}$K(p,$\gamma$)$^{36}$Ca reaction rate within the Gamow window of the X-ray bursts. New resonances have been observed in $^{36}$Ca by means of the one-neutron pickup transfer reaction $^{37}$Ca(p,d)$^{36}$Ca. The new rate is now well constrained.

With SPIRAL2, plans for direct low-energy measurements have been proposed, for example using the activation method, in particular with the very intense stable beams. Some ideas have also been proposed with the NFS neutron beam, for the measurement of the lifetime of some very long-lived nuclei ($T > 10^4$ years). In the long term, with $S^3$, the low-energy line and DESIR, one can envisage measuring masses of nuclei important for astrophysics (r-process).

The progress of the SPIRAL2 facility is described in detail in chapter 7 of this document.
**SPES**

The study of the reactions of astrophysical interest, essential for a quantitative understanding of element formation in the universe, is one of the main objectives of the research activity at SPES. The progress of the SPES facility is described in detail in chapter 7 of this document.

**HIE-ISOLDE**

Nuclear astrophysics research at ISOLDE is done with both low-energy and post-accelerated beams, and some examples of published work and recent proposals are given below. At the ISOLDE Decay Station (IDS), the $\beta$ decay of $^{208}$Hg into $^{208}$Tl was investigated, providing a unique test of the competition between allowed Gamow-Teller and Fermi, and first-forbidden $\beta$ decays, essential for the understanding of the nucleosynthesis of heavy nuclei in the rapid neutron capture process. IDS studies of $\beta$-delayed $\alpha$ decay have been able to constrain the reduced width of the bound $1^-$ level in $^{16}$O, with implications for the $^{12}$C($\alpha,\gamma$) reaction which is relevant for hydrostatic He burning. Mass measurements with ISOLTRAP have been important in several astrophysical problems. For example, recent measurements of the mass of $^{79}$Cu have shown it to be more bound than in models used to predict the composition of neutron stars, thus removing it as a possible component of neutron star crust. A recently accepted proposal plans to measure the excitation energy of the $5^+$ state in $^{128}$Sb via isomer and ground-state masses; the relative contributions of decay from these two states impact heating and photon emission following rapid neutron capture nucleosynthesis.

With a $^{206}$Hg beam accelerated by HIE-ISOLDE to 7.4 MeV/nucleon, single-neutron excitations in $^{207}$Hg have been probed with the (d,p) reaction using the new ISOLDE Solenoidal Spectrometer (ISS). The observed single-particle strength in $^{207}$Hg provides input to understand the structure of nuclei involved in the r-process path. ISS opens up several opportunities in nuclear astrophysics; a recent experiment measured the $^{61}$Zn(d,p) reaction to investigate the key rp-process reaction $^{61}$Ga(p,\gamma) via mirror symmetry.

The progress of the HIE-ISOLDE facility is described in detail in chapter 7 of this document.

**EURISOL**

EURISOL is described in detail in chapter 7 of this document.

We strongly recommend that the instrumentation needed for the implementation of the ELI-NP research program be built and the suggested experiments are performed with high priority.

Studies of the electromagnetic dipole response of p-nuclei will become possible with the use of the high-intensity small-dimension quasi-monochromatic gamma beam delivered by the VEGA System. The ELIADE gamma-ray array and the ELIGANT-GN setups are ready and will be used for such studies. The experiments will become possible in 2023 after the commissioning of the VEGA System. The ELISSA charged particle detector for photonuclear reactions of astrophysical interest consists of x3 position-sensitive silicon-strip detectors arranged in three rings of 12 detectors in a barrel configuration and 8 annular silicon-strip detectors covering the end-caps. The detector will cover more than 80% of the solid angle. The barrel is ready and the end-caps will be completed in 2022.

Furthermore, the high intensity gamma-beams provided by the coming ELI-NP facility will be useful for the precision study of the gamma-ray strength functions.

We recommend the formation of a target preparation network and the support of target producing research groups to enable successful future experiments.

This recommendation has led to a major element of the ChETEC-Infra Target Workpackage.

We strongly recommend the continuation and extension of the training efforts, at large and small-scale facilities, to guarantee enough skilful people at future facilities.

Training initiatives are developed at several facilities as well as schools to ensure education of skilful people at future facilities relevant for nuclear astrophysics. However, the COVID-19 crisis has had a significant impact on opportunities for gaining experimental expertise.
Some of the Schools organized within the Nuclear Astrophysics community are listed in the following:
the Russbach Winter School (Austria, Annual), the Catania Summer School (Santa Tecla, Italy, odd years), the Sinaia Summer School (Hungary, even years) and the Varna Summer School (Bulgaria, odd years) and the long running TALENT series of courses. Some of these schools were suspended due to the COVID-19 situation.

New initiatives have been proposed by the ChETEC-Infra community: the Intercontinental School on Nuclear Astrophysics (New initiative, ChETEC + IRENA + JINA, around Nuclei In Cosmos Conference), the Nuclear Physics in Astrophysics School (NPA conference, odd years). The SNAQS initiative (School on Nuclear Astrophysics Questions, monthly) successfully started during the COVID-19 pandemic.

We recommend support for ECT* at Trento to continue its leading role training young researchers in theoretical nuclear astrophysics.

ECT* is a unique centre in Europe bringing together the scientific community in theoretical nuclear physics and related areas, in the broadest possible sense. It typically runs 22 week-long workshops per year as well as a Doctoral Training Programme (3-4 weeks) and TALENT School (2 weeks, once every two years). Of the 86 workshops that ran since 2017 twelve were of direct relevance to nuclear astrophysics, and of these, eight were explicitly aimed at the role played by neutron stars and their mergers in nuclear astrophysics. The programme is determined by the Scientific Board, following suggestions by the scientific community. The number of visitors is around 800 annually. During the pandemic, ECT* made a successful switch to online delivery and adapted the facilities for hybrid meetings. It is expected that the post-pandemic meetings will remain hybrid, widening participation.

We recommend that the nuclear astrophysics community and funding agencies engage more proactively and effectively with the bodies influencing funding decisions on astronomical (both space and ground-based) facilities.

Since 2018 NuPECC initiated and followed several activities related to the funding of nuclear astrophysics and dedicated to tightening the links between nuclear astrophysics and astroparticle physics.

- NuPECC Task Force meetings (http://nupecc.org/?display=taskforce) with funding agencies include in its program all aspects related to the funding of nuclear astrophysics and related areas. The meetings aim at discussion and promotion of the implementation of recommendations of the NuPECC LRP 2017.

- A close collaboration of NuPECC with APPEC and ECFA with mutual participation in general meetings of the three committees allows for participation in the elaboration of the strategic plans for particle, astroparticle and nuclear physics and better understanding of underlying funding mechanisms.

- A dedicated series of joint APPEC, ECFA and NuPECC seminars (JENAS http://nupecc.org/jenaa/?display=seminars) and in particular the resulting Expressions of Interest on Gravitational Waves and Dark Matter (see http://nupecc.org/jenaa/?display=eois) aim at a direct enhancement of close collaborations between the nuclear astrophysics and astroparticle physics communities. The JENA Seminars involve funding agencies of the three communities with an opportunity to discuss funding of the three research areas.
5. Symmetries and Fundamental Interactions

The LRP recommendations related to Symmetries and Fundamental Interactions (SFI) contain several rather generic topics (funding of university groups, support for theory, trap and beam development) which are difficult to assess without performing a Europe-wide survey. There are, however, indications that the support in these topics is in general continuing and in the field of theory positions exist and are filled with excellent young scientists. Trap and beam developments are being done by various groups, without strong coordination but very successfully.

A second class of recommendations concerns support for specific facilities where experiments are performed. Some of them are primarily used for studies of SFI within NuPECC (AD/ELENA, ILL, FRM-2 and ESS, the storage rings with highly charged ions at GSI/FAIR, underground facilities), some are shared with other communities in nuclear physics (radioactive beam facilities, PSI, electron scattering facilities). Their description can be partly found in chapter 7, here we focus on the aspects concerning SFI.

For the exotic systems to be investigated, dedicated laboratories with intense sources are indispensable. The following facilities are of vital importance for our field and should be continuously supported.

The primary recommendation on SFI concerns the AD/ELENA facility at CERN. This is developing in an excellent way. ELENA has started operation providing antiprotons at 50 times lower energies to the experiments in August 2021, after a CERN shutdown which was extended due to the pandemic. Two new experiments were approved while one has been discontinued. The current experiments continue to produce excellent results since the publication of the LRP, with several optical and microwave transitions observed for the first time ever in antihydrogen by ALPHA. The BASE collaboration measured the antiproton magnetic moment with ppb precision in 2017, the charge-to-mass ratio to 16 ppt in 2022, and extended their techniques to study Dark Matter using trapped antiprotons. Both ALPHA and BASE are working on sympathetic cooling of (anti)protons and positrons with Be ions in order to obtain higher precision. ASACUSA is making continuous progress towards forming an intense antihydrogen beam for hyperfine spectroscopy.

The AEGIS, ALPHA and GBAR experiments are preparing for the first sensitive measurements of antimatter gravity which are likely to produce results in the coming years. The newly approved experiments will use portable traps aiming at either increased precision (BASE-STEP) by removing antiprotons to a low-noise location or bringing antiprotons to ISOLDE for nuclear structure studies using antiprotonic atoms (PUMA) which will bring together two fields within NuPECC.

The AEgIS, ALPHA and GBAR experiments are preparing for the first sensitive measurements of antimatter gravity which are likely to produce results in the coming years. The newly approved experiments will use portable traps aiming at either increased precision (BASE-STEP) by removing antiprotons to a low-noise location or bringing antiprotons to ISOLDE for nuclear structure studies using antiprotonic atoms (PUMA) which will bring together two fields within NuPECC.

Cold and ultra-cold neutron facilities

In September 2021, the governments of France, Germany and the United Kingdom signed a protocol that will extend their support of the Institut Laue-Langevin (ILL) for another ten-year period from 2024 to 2033, and the FRM-II reactor in München will start operating the facility PERC for fundamental physics with neutrons in the near future. The realization of the European Spallation Source (ESS) was recommended and is ongoing, there is however a struggle for the community to ensure a continuing operation of the existing facilities until ESS is fully functional in 2029. So far, the availability of cold and ultra-cold neutrons for nuclear and particle physics, which is essential to sustain an active community in this field, is not ensured at ESS.

Radioactive beam facilities

Since the publication of the NuPECC 2017 LRP, there have been a number of achievements and significant progress in the field of searches for new interactions and tests of fundamental symmetries.
using radioactive nuclei, primarily by precision measurements in nuclear beta decay. WISArD at ISOLDE measured correlations between the beta particle and the recoiling ions for several decay branches in the decay of $^{32}$Ar which are sensitive to both the beta-neutrino angular correlation parameter and the Fierz interference term. The pure Gamow-Teller branches have been used for the first time and enable constraints on Tensor couplings to be extracted. A new proposal has been initiated at GANIL within the bSTILED project. The goal is a high precision measurement of the beta energy spectrum in $^6$He decay, by implementing calorimetry techniques using both the low energy (25 keV) and the high energy (260 MeV) beams of $^6$He available at GANIL. The MORA project led by GANIL/LPC Caen and hosted at JYFL in Jyväskylä searches for new sources of CP violation through the measurement of the $D$-triple correlation coefficient in the decay of vector polarized $^{23}$Mg$^+$ ions. The ions will be stored in a transparent Paul trap and polarized by suitable laser pumping transitions. The beta particles and recoil ions will be detected with several beta-telescopes and micro-channel plates located around the trap. The project is expected to commission a large part of the setup in 2022. On the phenomenology front, a new global analysis of the most precise and relevant data in nuclear and neutron beta decays has been published, improving constraints by factors of up to 2.8 in more general scenarios.

**The storage and trapping facilities HITRAP, CRYRING, and ESR**

All parts of modular start version of FAIR substantially enlarge the research capabilities of FAIR for the exploration of matter under extreme conditions and have key features that offer a range of novel and challenging research opportunities for quantum, astrophysical and fundamental research using highly-charged ions and exotic nuclei as promoted by the SPARC collaboration. In 2020/2021, emphasis was given to the very first storage-ring experiments at the ESR after a long interruption period of several years as well as to the commissioning of CRYRING@ESR (a Swedish in-kind contribution to FAIR). Full commissioning of the ring is in progress and the very first experiments have already proven the concept of CRYRING@ESR with heavy ions from the GSI accelerator chain. Moreover, for 2022 it is planned to commission the trapping facility HITRAP with beams from the ESR aiming at high precision experiments (e.g., bound-state g-factor, hyperfine-structure studies, mass measurements) for the heaviest highly-charged ions and exotic nuclei at rest in the laboratory.

**Paul Scherrer Institute**

At PSI, experiments with muonic atoms determining charge radii and other nuclear moments and a first laser spectroscopy experiment of pionic hydrogen aiming at a determination of the pion mass with largely increased precision have been performed. The most precise value of the neutron EDM experiment has recently been obtained and an improved experiment is being prepared. In future, the high intensity muon beams of the IMPACT project planned to be implemented in 2025-2028 are of biggest importance, providing muon beams with two orders of magnitude higher intensity.

**MESA**

In the context of SFI, experiments at MESA are planned to measure the weak charge using parity-violating electron scattering, and to more precisely determine the proton radius using electron scattering. In addition a beam dump experiment is planned to search for dark photons (“DarkMESA”) with up to $3 \times 10^{22}$ electrons on target, which will be the highest number available among similar experiments. This project is well advanced including an existing detector concept.

**DAΦNE**

The program of DAΦNE is also described in chapter 7. Relevant for fundamental interactions is the SIDDHARTA-2 experiment aiming at a first measurement of the strong-interaction induced shift and width of the 2P-1S transition in kaonic deuterium yielding information on the kaon-nucleon scattering length in the neutron sector. The experiment is being prepared and will start data taking in 2022.

**Underground laboratories**

The Italian underground laboratory LNGS (Laboratori Nazionali del Gran Sasso) hosts, among many small R&D projects, several large world-leading experiments on solar neutrinos, search for neutrinoless double beta decay and direct search for dark matter. For example, the BOREXINO experiment, which
is coming to an end, not only precisely measured all neutrinos from the pp chain, but recently discovered CNO neutrinos for the first time. GERDA has been successfully completed and has achieved the longest half-life limit for the neutrinoless double beta decay and a follow-up experiment, LEGEND-200, is being built. CRESST has achieved the world's best sensitivity for light WIMPs and the XENON1T experiment for medium and heavy WIMPs in recent years. The direct search for dark matter at LNGS continues with CRESST-III and the recently launched experiment XENONnT and soon with DarkSide-20k. The smaller underground laboratories LSM (Laboratoire Souterrain de Modane), Canfranc (Laboratorio subterráneo de Canfranc) and Boulby (Boulby Underground Laboratory) host (except for the EDELWEISS experiment at LSM, which has similar goals as the CRESST experiment), smaller experiments that are mainly for future partly interdisciplinary R&D projects. Currently, parts of the scientific infrastructure of the LNGS are being modernised and extended in a joint German-Italian agreement (in combination with a project at FAIR). For the other smaller underground laboratories, expansion plans are often mentioned, but not yet realised.

The final recommendations, analogous the very first ones, ask for generic support and access:

**Upgrades and support of existing small facilities** as well as large scale infrastructure in Europe, including underground laboratories and accelerators, should be continued.

**Sufficient access and beam time** should be provided, as this is mandatory to push the limits of the present best experiments and to allow for new dedicated setups.

**R&D for new initiatives** should be vigorously pursued.

As before, there is no indication that these recommendations were not followed on a large scale.
6. Applications and Societal Benefits

Nuclear Physicists are mobilised to answer fundamental needs and questions addressed by society specifically on energy, health, knowledge and protection.

a) For nuclear energy systems the development of predictive and reliable models and simulation tools is mandatory. This implies a strong cooperation between experimentalists, theoreticians and evaluators. The DEMO-Oriented Neutron Source (IFMIF/DONES) and the ADS demonstration project MYRRHA at SCK CEN will be important in this domain.

Collaborative efforts to improve data relevant for nuclear energy have been developed. The involvement of international institutions such as the IAEA and the Nuclear Energy Agency of OCDE has been very important to set up a Joint Evaluated nuclear data Library for Fusion and Fission (JEFF). The Horizon 2020 program has supported several projects: SANDA, which is focused on the safety of European nuclear installations, and ARIEL, which provides transnational access to a variety of neutron facilities across Europe.

The first phase of the MYRRHA demonstration project is being currently implemented. The JEFF collaboration was central in assessing and addressing nuclear data needs for the MYRRHA project. A collaboration agreement between SCK CEN and the Joint Research Centre (JRC) of the European Commission focused on the neutron-induced cross section for lead and bismuth.

The DONES project is progressing on the design and validation. The preparatory phase is funded by the EU through the project DONES-PrepP (https://ifmifdones.org/en/dones-program/dones-prep/). Even though it is a project mainly driven by fusion-related applications a significant effort is being made to identify and integrate nuclear physics experiments in the facility design. This effort is being carried out in close collaboration with the European nuclear physics community.

b) It is important to continue the development of adapted techniques for cancer treatment. In particular, efforts should be made for the production of specific radio-isotopes and more efficient imaging techniques in strong collaboration with the end-users.

The International Biophysics Application (www.gsi.de/bio-coll), based at GSI/FAIR, includes all running and planned accelerators with programs in biomedical sciences (e.g. GANIL, PARTRAC, INFN, NICA, iThemba, ELI,..). The collaboration has demonstrated the opportunities of the new accelerators both in terms of high energy (useful for space radiation protections, a topic strongly supported by ESA) and high intensity. High particle fluxes allow novel applications such as FLASH, mini-beam radiotherapy, and use of radioactive ion beams for simultaneous treatment and imaging, an application awarded with an ERC Advanced Grant in 2020. The infrastructure program on heavy ion cancer therapy (HITRI+, https://www.hitriplus.eu), is funded by the EU and involves the relevant European facilities.

Regarding imaging techniques, there have been important advances on basic nuclear detector development and data processing (electronics and software), although they have yet to materialize on a significant increase on PET resolution. A time resolution of 10-ps for PET has been mentioned as a challenge to be achieved.

c) With the availability of high-intensity accelerators and new installations (GANIL, ESS, FAIR, ISOLDE) new studies in materials science, atomic and plasma physics will be possible, exploring matter in extreme conditions. Some of these installations will also be used to study and develop the production of new radioisotopes for medical use.

Higher intensity beams that will be produced in the frame of the NEWGAIN (NEW GANIL Injector) project, recently funded by the French National Research Agency, will allow to reach high fluencies expected, for example, in the simulation of high-power targets of accelerator facilities, and may be used for new studies in material science.

The GSI-FAIR storage and trapping facilities HITRAP, CRYRING, and ESR (all part of the modular start version of FAIR), will substantially enlarge the research capabilities of FAIR for the exploration...
of matter under extreme conditions. The proton microscope PRIOR at FAIR offers 10 micrometre resolution for plasma studies, while the heavy ion microprobe at UNILAC-X0 provides sub-micron resolution for radiation tests.

The upgrade of detectors at ISOLDE, as well as the use of polarized radioactive beam has allowed to study energy-efficient perovskite materials, as well as to improve the use of magnetic resonance techniques in biological systems. The EU infrastructure project for microelectronics irradiation RADNEXT is coordinated by CERN and provides transnational access to the relevant European facilities.

A dedicated facility CERN-MEDICIS started producing radionuclides in 2018 for the biomedical research in targets located in the beam dump using the proton beam delivered to ISOLDE, and purifying radionuclides by isotope mass separation, techniques that have been developed over the past 50 years. The new LINAG at GANIL is now able to deliver intense beams of p, d and alpha particles, which will produce innovative radio-isotopes relevant for targeted alpha therapy. The French-funded project REPARE is ongoing with the main aim to optimize the production of $^{211}$At. Other facilities are foreseen to come online soon (ISOLPHARM at LNL). EU funded programs (MEDICIS-Promed, PRISMAP, EURAMED Rocc-N-Roll) indicate the strong support for this research area.
7. Infrastructures

Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

Since the breaking of ground for the central SIS100 accelerator of FAIR (https://fair-center.eu) in mid-2017, the site was transformed into a vibrant construction area with most buildings either constructed or under construction. In particular, concrete works for the SIS100 double-ring tunnel, which is 17 m below ground, have been successfully concluded and the adjacent buildings for the transfer of beams and the CBM cave are to a large extent built. Civil works are now in full swing in the southern areas, including the buildings for the Super-FRS, the APPA cave and the anti-proton production target. The next step will be the installation of the Technical Building Infrastructure (TGA). Still pending is the construction of the comparably simpler buildings for CR, HESR and p-Linac, for which funding commitments are awaited. The construction of accelerator components also progresses swiftly for all accelerators and ancillary systems. As such, the series production and series tests of all SIS100 dipoles and RF cavities has been successfully completed and most components for the HESR are stored after manufacturing and testing.

All experimental collaborations have made huge progress in building the components to perform experiments at FAIR. Prominent examples are:

- The successful installation, commissioning and operation of CRYRING including experiments for APPA.
- The set-up and successful operation of mini-CBM, which comprises prototypes/first-of-series modules of all CBM detectors.
- The delivery, commission and scientific experiments with the large superconducting GLAD magnet for NUSTAR R3B.
- The completion of the large, segmented PANDA solenoid yoke with opening doors.

The FAIR Phase-0 program, started in 2019, includes progressively many new or upgraded components for FAIR both for the accelerators and the experiments, although operated in pre-existing GSI halls. FAIR Phase-0 includes about 3 months of beamtime per year during which, also thanks to parallel operation of up to seven different experiments, a variety of world class research projects are carried out. The relevance of this programme can be seen by the huge positive response to the calls for proposals. The scientific community has very enthusiastically welcomed this opportunity and the experiments’ scientific outcome will become evident in the coming years, when results will be published.
In 2025, early science experiments in the newly built halls for FAIR are expected to commence utilising SIS18 beams in Super-FRS and the APPA cave. First experiments with beams from the SIS100 are expected to take place in 2026 and - assuming pending funding is provided by the shareholders by mid 2022 - all experiments are expected to be in operation until 2028.

Recommendation 2: Support for construction, augmentation and exploitation of world leading ISOL facilities in Europe (SPIRAL2, SPES, HIE-ISOLDE, EURISOL status and future plans)

**SPIRAL2**

The Système de Production d’Ions Radioactifs en Ligne de 2e generation (SPIRAL2) is a new facility to extend significantly the actual possibilities of Radioactive Ion Beam (RIB) physics and related applications. SPIRAL2 is part of the GANIL infrastructure, which is the largest research infrastructure in Lower Normandy (Caen, France) and one of the largest in France.

Under construction since 2005, the linear accelerator (LINA) of SPIRAL2 was commissioned in the period 2015 - 2019 and it has been delivering science since 2021 with proton and deuteron beams of nominal energies (up to 20 MeV/nucl.) and intensities (up to 5mA) as well as a high-flux of fast neutrons. Partial commissioning (ion-source and RFQ) of the LINA with heavy-ion beams (4He, 16O) was successfully accomplished in 2015 and full commissioning of heavy-ion beams is foreseen in 2022. In 2021 a second heavy-ion injector for the SPIRAL2 LINA with a maximum A/q of 7 (NewGAIN project) was funded via a French EQUIPEX grant. It is expected that this injector largely increases the heavy-ion beam intensities of ions with A≥ 40 and will enter into operation by 2027.

The three experimental areas served by the LINA are: NFS, which produced its first test neutrons in December 2019, S3 (Super Separator-Spectrometer), which is presently in the final construction phase, and DESIR (Experimental hall for experiments with low-energy RIB produced at S3 and SPIRAL1), which is in its final design and integration phase. The NFS experimental program began in September 2021. S3 is expected to start its commissioning phase with beam by mid 2023 and to start its first experimental campaign in 2024 providing low energy RIB, while DESIR envisages early science operation by 2027.

In conclusion, since the publication of the 2017 LRP, the SPIRAL2 facility in its first phase was partially completed (high-power LINA and NFS facility) and operates with light-ion beams. Two other experimental rooms, S2 and DESIR, and a second injector for LINA are in the construction phase. The decision on the construction of SPIRAL2 Phase 2 with production of high-intensity thick-target ISOL beams was postponed by French funding agencies in 2015. Further evolution of GANIL-SPIRAL2 beyond the currently accepted projects is expected to be defined in the coming few years.

**SPES**

The SPES project for an ISOL facility at the Legnaro National Laboratory is in an advanced installation phase heading towards completion. Successful acceptance tests of the new cyclotron were accomplished in 2017 and in 2021 the Target Ion Source complex was installed in the ISOL bunker, with final auxiliary equipment to be completed in 2022. The first commissioning operation of SPES is expected to be carried out at the beginning of 2023, with the production of low-energy radioactive beams for experiments.
In 2021 the assembly of the different components of the ALPI post-accelerator for RIB’s started with the completion of installation of all RFQ modules expected in 2022. Final Charge Breeder tests are expected to be completed at the end of 2023, such that post-accelerated radioactive beams from ALPI are expected in 2024.

**Intensity and Energy upgrade of HIE-ISOLDE (+storage ring)**

One aim of the HIE-ISOLDE upgrade of the ISOLDE facility at CERN has been realized in the period 2014-2018: the radioactive beam energy has been increased from 3.1 MeV/u (from the REX-ISOLDE linac) up to 10 MeV/u by extending the accelerator with 4 superconducting modules. Also, two more beam lines for experimental stations were installed. The second aim, reconstructing the target area and proton transport lines such that a potentially higher proton intensity (x2) and energy (from 1.4 to 2 GeV) from the PS Booster could be sent onto the ISOLDE targets, has not yet been realized. Currently, a study is ongoing to replace the 30 year-old beam dumps first. The intensity upgrade will yield higher radioactive isotope yields for the majority of the more than 1000 isotopes produced at ISOLDE, and might be realized during CERN’s next long shutdown in 2025-26, provided funding can be secured.

During two workshops in 2019 and 2020, ideas to fully Exploit the Potential of ISOLDE at CERN (EPIC), have been discussed. These included the need for an additional ISOLDE building, along with additional high-power target stations. Such an addition would allow the expansion of both the low-energy and high-energy experimental areas to host new experimental stations, such as a newly-proposed compact heavy-ion storage ring and a trap for anti-protons interacting with RIB’s, amongst other developments.

**EURISOL and EURISOL-DF**

EURISOL as defined in the FP6 Design Study documents, including the high power (Mega Watt) target, is together with FAIR, a major aim of the Nuclear Physics community in Europe. In view of the delays being experienced by the ‘pre-runner’ facilities (as defined in the NuPECC long range plan 2004), and of the fact that there is today no main candidate to construct, finance and host EURISOL it was considered to modify the European strategy in agreement with the NuPECC 2017 LRP with an intermediate and ambitious step: the EURISOL Distributed Facility (EURISOL-DF) [http://www.eurisol.org/eurisol_df/](http://www.eurisol.org/eurisol_df/).

EURISOL-DF aimed at enhancing complementarities and avoiding duplication of efforts in the RIB developments at ISOL facilities in Europe. It would have also largely enhanced competiveness of the European nuclear science and its applications at the global level.

**Members**

The EURISOL-DF membership was open to all European RIB facilities. Initially the members of the EURISOL-DF were GANIL-SPIRAL2, HIE-ISOLDE and LNL/INFN -SPES.

The ISOL@MYRRHA facility is a candidate for the future full member of EURISOL-DF.

EURISOL-DF should closely collaborate with FAIR facility (Darmstadt, Germany) and with smaller scale EU ISOL facilities: ALTO (Orsay, France) & JYFL (Jyväskylä, Finland)

**Organisation**

In 2014 the EURISOL MoU was already signed by GANIL (France), CERN, COPIN-IFJ (Poland), SCK-CEN for Belgian EURISOL Consortium (BEC) and INFN (Italy).

In the initial phase of the EURISOL-DF a coordination of actions leading to the preparation of proposal for the EURISOL-DF was ensured by the EURISOL MoU Steering Committee.

In the period 2016-2020 the EURISOL MoU Steering Committee initiated and coordinated in close collaboration with the EURISOL User Executive Committee an intensive preparatory work for EURISOL-DF to be proposed as distributed facility for the 2021 ESFRI roadmap. Dedicated Steering Committee and Working group meetings, conferences (EURISOLL-DF in Leuven in 2016 EURORIB 2018), EURISOL Town meetings (2017 in Lisbon, 2018 in Pisa) and meetings with funding agencies of concerned countries and infrastructures were organized.

Technical R&D work related to EURISOL & EURISOL-DF was also continued and accomplished in the framework of dedicated Joint Research Activity of the ENSAR2 H2020 project from 2016 to 2021 (https://www.ensar2.eu ).
A clear interest and declaration of involvement in the EURISOL-DF project were expressed by several partners (INFN Italy, CEA France, GANIL France, SCK-CEN & ISOL@MYRRHA Belgium, COPIN Poland). The project was partially supported by ISOLDE Collaboration and JYFL Finland.

However, two major partners namely IN2P3 France (managing ALTO facility and co-managing GANIL) and CERN (hosting ISOLDE) did not agree to support the project. Despite intense negotiations with these two partners it was not possible to obtain their support and the EURISOL-DF project was closed by the EURISOL Steering Committee in January 2020.

At this meeting a new idea emerged to create a league of all EU RIB facilities. Due to COVID-19 pandemic activities towards the organization of the league of EU RIB facilities were postponed.

Support for the full exploitation of existing and emerging facilities

The up-coming ESFRI facility ELI-NP with a worldwide unique gamma-beam quality and high-power lasers will address key questions in nuclear structure, astrophysics and various applications. Completion of the facility and instrumentation is mandatory.

The ELI-NP research infrastructure is in the processes of gradual transition from implementation to operation. The status can be summarized as follows:

- The high-power laser system has been fully functional at the design parameters since 2020. The largest power output of 10 PW and its transport to the experimental setups were demonstrated.
- The experimental setups will gradually enter in operation; first commissioning experiments will be performed followed by open access user experiments based on proposals evaluated by a PAC. The schedule for the start of user experiments operation mode with high power lasers is: 100 TW in Q2 2022, 1 PW in Q3 2022 and 10 PW in Q1 2023. Final commissioning for users by the end of 2023.
- The Variable Energy GAmmma (VEGA) System will be completed by summer 2023, followed by commissioning runs with expert users in the second half of 2023. Open access user experiments selected by a PAC will start in 2024.

For the up-coming NICA facility complete construction to study hot and baryon rich matter in heavy ion collisions at $\sqrt{s_{NN}} = 4 - 11$ GeV. Develop and bring into operation the programme on BM@N, MPD and SPIN detectors as well as put into operation the SHE factory to search for a new stability regime for nuclei with $Z$ beyond 118 (Og).

The mega-science “NICA Complex” project is being implemented at the Joint Institute for Nuclear Research (JINR). Building construction works were completed at the end of 2021. At the end of 2020, the first beam circulation in the NICA complex Booster was successfully obtained. In the technical run in September 2021 beam extraction and beam transportation from the Booster to the Nuclotron was achieved. It gave an opportunity for the fixed target experiment BM@N to start preparation for the heavy ion run in April 2022. The SPD detector team, having presented the CDR, began work on the technical project and prototyping. The production and commissioning of the MPD detector's subsystems is advancing well to register the first beam collisions in the NICA collider at the end of 2022.
The new SHE Factory at FLNR/JINR began operation at the end of 2020 providing high intensity heavy-ion beams at a few MeV/n for production and study of heavy and super-heavy elements. Experiments on synthesis of new elements $Z=119$ and $Z=120$ are expected to begin in 2022.

Exploit the facilities DAΦNE, ELSA, GSI, MAMI and PSI for rich programmes on hadron interactions and on hot baryonic matter.

The European users community in hadron physics at these facilities receives funding from the EC in the framework of “Integrating and opening research infrastructures of European interest” within the STRONG2020 consortium in order to facilitate user access. A particular role in the project is played by the research infrastructures, among the most important ones in the field of particle physics in Europe: COSY, MAMI, LNF, FTD/ELSA, GSI, ECT*, CERN.

- DAΦNE started operations for the SIDDHARTA-2 experiment in February 2021 and was regularly in collision mode by the end of April 2021; at the same time, the set-up of SIDDHARTA-2 was completed and was ready to take data in a reduced configuration.
- Within the last few years at ELSA, the CBELSA/TAPS experiment published several new results, which include, for example, (double) polarization measurements of eta mesons. The BGO-OD experiment started data taking and was able to publish first results for different final states containing strangeness.
- HADES, mini CBM and WASA@FRS at GSI devoted are to research on hadrons and hot baryonic matter. HADES had a very successful physics run in 2019, collecting more than 14 billion events in Ag+Ag collisions. Mini CBM is the demonstrator platform of the CBM experiment at FAIR was taken into operation in 2020. The WASA detector, formerly at COSY in Jülich, is currently installed at the FRS. Hadron physics at GSI is being further strengthened by the transfer of FAIR-related activities of the IKP in Jülich to GSI. Operation of COSY will continue until the end of 2024.
- At MAMI, a three-spectrometer setup (A1) is complemented by a tagged photon beam facility (A2). In the MAMI injector, spin-polarization vertical to the scattering plane has been achieved for the A1 setup using special solenoid settings. The setup of a new electron accelerator employing energy recovery at 105 MeV is presently prepared (MESA) and is expected to provide beam for experiments in 2024.
- The high intensities of low energy pions, muons and ultracold neutrons (UCN) at PSI have been in very high demand. A new measurement of the proton charge radius is under way by the MUSE experiment comparing simultaneously muon and electron scattering and using both polarities. With UCN, the search for the electric dipole moment of the neutron provided a new best upper limit and propels the activities for a next improved measurement. Motivated by fundamental physics, material science and medical applications, the IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target technology) project at PSI aims at constructing a high intensity production facility of radio-isotopes for novel medical theragnostic applications, as well as for two high intensity muon beams of unprecedented intensities, a factor 100 above the present leading beamline.

Exploit the facilities ALTO, GANIL-SPIRAL2, GSI-FAIR, IFIN-HH/ELI-NP, ISOLDE, JYFL, KVI-CART, LNL-LNS, NLC Warsaw-Krakow, mainly devoted to nuclear structure, nuclear astrophysics, reactions and applications.

All facilities have provided beam time as planned, and were supported through the ENSAR2 research infrastructures H2020 program of the EU from June 2016 till August 2021. In the final report, currently under approval of the European Commission, a review of the achievements at each facility will be available. In general, all facilities have fulfilled and, in several cases, even exceeded their initial commitments in terms of the beam hours number of performed experiments and supported external users. Due to the COVID-19 pandemic ENSAR2 was extended three times from March 2020 to August
2021, reflecting the partial or total shutdowns of the most of the facilities in the first half of 2020 and also difficulties to host external users in 2020 and 2021. Several facilities have operated in the period 2016 – 2021 with additional constraints related to the construction of new facilities (e.g. GANIL-SPIRAL2, GSI and LNL) or long shut down of the accelerator complex (ISOLDE).

Exploit the small-scale existing facilities devoted to specific topics in nuclear physics and applications. Among them LUNA-MV@LNGS, nTOF@CERN, ELENA@CERN and NP@ILL are worldwide unique.

**LUNA**

Over the last 4 years, several processes relevant to the CNO, MgAl and NeNa cycles have been studied using the LUNA 400 kV machine, which has been operational since 2001. LNGS-INFN is currently expanding the accelerator laboratory by installing a new 3.5 MV machine that will be equipped with two independent beam-lines. The new accelerator was installed underground at LNGS in the fall 2021, with initial scientific exploitation foreseen by 2023.

**ILL**

The FIPPS instrument was fully commissioned and its array of clover Ge detectors was equipped with anti-Compton shields. An active fission target based on liquid scintillators provided considerably improved sensitivity for spectroscopy of fission products and an alternative design based on diamond detectors is under development. Fast timing and conversion electron spectroscopy experiments are regularly performed with mass-separated fission products at the LOHENGRIN spectrometer. Precision measurements of free neutron decay with the spectrometer PERKEO installed at the PF1B cold neutron beam line provided constraints on the Standard Model. The gravity resonance spectrometer qBounce using ultracold neutrons from the PF2 source provided strong constraints on Chameleon and symmetron dark energy models respectively. The neutron interferometer S18 is being used for fundamental experiments on quantum-mechanical phenomena. A site is now being prepared to accommodate the RICOCHET experiment that will study coherent elastic neutrino-nucleus collisions. The V4 high flux beam tube is regularly used for production of radionuclides with high specific activity, enabling new applications in basic science and medicine.

**nTOF@CERN**

The nTOF facility went through an important update during CERN Long Shutdown 2 (2019-2021). The neutron spallation target and moderator assembly has been completely re-designed, built and commissioned during the 2021 run (generation #3 target). The much-improved performances of the neutron beam characteristics in the second experimental area (EAR2) and at the new experimental area set at very short distance (approx. 3 m) from the spallation module (NEAR Station) are expected.

**ELENA@CERN**

The recently fully commissioned ELENA facility at the AD provides an antiproton beam at 100 keV (stable in beam position and in intensity) that is guided to a number of experiments (AEgIS, ALPHA, ALPHA-g, ASACUSA, BASE< GBAR, PUMA) via electrostatic transfer lines. Antiprotons injected from the AD are separated into 4 bunches, each of which can be sent to a different experiment after deceleration in ELENA, thus leading to the parallel operation of at least four experiments around the clock over the typical beam availability period of 6-8 months annually. In addition to the main focus of AD experiments on antihydrogen and antiproton precision studies, three experiments also focus on nuclear physics: ASACUSA, AEgIS and PUMA. In the case of ASACUSA, antiproton-induced nuclear fragmentation studies have been carried out. In parallel to its antihydrogen program, AEgIS is preparing a physics program based on pulsed formation of antiprotonic atoms in vacuum. Finally, PUMA is a hybrid apparatus whose goal is to interact trapped antiprotons (obtained at ELENA) with short-lived radio-isotopes (at ISOLDE), using the annihilation of antiprotons with nucleons in order to study the nuclear periphery.
Support for ALICE and the heavy-ion programme at the LHC with the planned experimental upgrades.

The heavy-ion programme at the CERN Large Hadron Collider is uniquely suited to determine the properties of the Quark Gluon Plasma at high temperature. Progress relies on new and larger data samples, which are needed for more precise and differential measurements. The experimental programme aims to fully exploit the high-energy collisions which will be delivered by the LHC in Run-3 and Run-4. We consider it crucial that all aspects of the LHC heavy-ion programme, including manpower support and completion of the detector upgrades, are strongly supported.

ALICE is an experiment designed to study the physics of strongly-interacting matter and the quark-gluon plasma in nucleus-nucleus collisions at the Large Hadron Collider. The ALICE collaboration currently includes over 1000 authors from 176 institutions in 40 countries.

The CERN Long Shutdown activities proceed according to the plan. In particular, the installation of the new detector was completed, and its commissioning is ongoing according to the plans. The newly installed detectors were pre-commissioned and the whole ALICE setup entered the global commissioning phase in July 2021. The commissioning includes the complete chain of the O2 system from the readout electronics through FLP, EPN, storage, and the computer software. At the same time, the physics data processing software system undergoes tests and performance optimizations. In essence, despite the circumstances of the COVID-19 pandemic with a reorganised workforce it was possible to complete the ALICE installation and pre-commissioning activities and start global commissioning according to the plans. Along with the preparations for the LHC restart in 2022, ALICE is preparing to take advantage of the LHC beam tests expected to take place in the last week of October 2022.

New instrumentation foreseen for LHC Run 4 - the so-called ITS3 and FoCal is under development. A Letter of Intent for a new ALICE 3 detector that would enable taking full advantage of the heavy-ion collisions in LHC Run 5 and beyond is under preparation. The new experiment aims to advance the characterization of the properties of QGP beyond the potential of Run 3 and Run 4 using rare heavy-flavour hadrons and the variety of electromagnetic probes mapping the time evolution of the system. The planned instrumentation features wide rapidity coverage with a tracker entirely based on the Monolithic Active Pixel Sensors (MAPS) with a compact design of about 1.6 m diameter and 8 m length. The tracker will be accompanied by detectors providing hadron, electron and muon identification.

The rich LHC physics harvest continues to span key areas of ALICE scientific interest. This includes particle correlations in the soft sector (that allow us to study QGP properties but also to make unique contributions to the understanding of the strong interaction among pairs of hadrons). Recent results include latest measurements of jets and heavy-quarks in the hard processes domain and on the production of resonances in pp collisions. The results span across collision systems from pp, through p-Pb, to heavy-ions featuring Pb-Pb and Xe-Xe collisions including the photon mediated collisions - the so-called ultraperipheral collisions.

Support to the completion of AGATA in full geometry

AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in the long-term must be fully completed in full 60 detector unit geometry in order to realise the envisaged scientific programme. AGATA will be realised in phases with the goal of completing the first phase with 20 units by 2020.

Building on two decades of collaboration around the EUROGAM and EUROBALL gamma ray multi-detectors and fruitful R&D under the auspices of the 5th framework program of the European Union, in 2003 several European countries established a new collaboration called AGATA (Advanced GAmma Tracking Array). The objective was to demonstrate the feasibility of gamma-ray tracking and, subsequently, to build the 4π spectrometer. The AGATA spectrometer has just completed its first phase of construction, which corresponds to 1/3 of the total coverage (up to 20 detection units, up to 60 capsules). Since 2010, this phase has been accompanied by measurement campaigns at LNL in Italy, at GSI in Germany and from 2014 until summer 2021 at GANIL, in Normandy, France. In September 2021, AGATA moved to LNL, Italy. The start of the campaign at LNL is scheduled for spring 2022.

The AGATA MoU was renewed in 2015 (signed in 2018 and extended until the end of 2020). The new MoU, called AGATA Phase 2, covers a 10 years period from 2021 to 2030 with the aim to build a 3π
configuration (135 capsules). The MoU confirms that the final goal is a construction of $4\pi$ array (180 capsules).

The scientific output from the project has reached 138 publications with 11 high impact letters and 1 Nature Physics article published with data from AGATA experiments on the 3 experimental sites. A review of the experimental results can be found in https://doi.org/10.1016/j.ppnp.2021.103887.

Perform R&D programmes for possible future facilities specified below.

In order to lay the foundations for exciting new science opportunities in the long-term future, the respective communities must vigorously pursue coordinated research and development programmes, in the areas listed and assessed below.

**Precision Storage Ring to search for Charged Particle EDM based on ongoing COSY studies**

The JEDI collaboration is performing R&D in preparation of a precision storage ring for polarized proton and deuteron beams. A precursor experiment with polarized deuterons has been conducted at the Cooler Synchrotron COSY (Jülich). A Charged Particle EDM collaboration (CPEDM) has been initiated within the CERN Physics-beyond-Colliders initiative and the project has been recognized by the ESPP Update of 2020. An expression of interest has been submitted to JENAS.

**Antiproton Polarizer Ring: an upgrade of HESR at FAIR**

No further experimental investigations concerning the provision of a high-intensity polarized antiproton beam have been conducted. Plans are to resume this effort when antiproton beams become available.

**Sympathetic laser cooling techniques for protons, anti-protons and highly-charged ions**

In a partly coordinated effort, several groups worldwide (including CERN, RIKEN, GSI, Hannover, Heidelberg, Mainz,...) are developing a sympathetic cooling scheme using laser-cooled $^9$Be+ ions. The BASE collaboration at CERN recently achieved proton cooling, which will later be applied to antiprotons and also sympathetic cooling of highly-charged ions has been realized. An ITN to get the related efforts supported by the European union has been applied for.

**The design of advanced high intensity lasers for precision spectroscopy of exotic atoms, such as antihydrogen, muonic hydrogen, pionic helium, and muonium;**

No officially coordinated effort exists so far regarding the development of high-intensity lasers, but individual groups are making progress. The exotic atoms community has successfully carried out laser spectroscopy of antihydrogen and pionic helium.
Development of highly stable and well-defined magnetic fields and accurate high precision magnetometry needed for EDM and novel dark matter search

Significant progress has been made recently by the nEDM collaboration searching for a neutron electric dipole moment at the Paul Scherrer Institute (based on optically pumped Cesium magnetometers). On-line accuracy of 45 to 90 pT and stabilities of about $5 \times 10^{-9}$ have been reached.
8. Theory

With ongoing major conceptual and computational advances, nuclear theory plays a crucial role in shaping existing experimental programmes. Combining theory initiatives in a concerted effort is essential for optimal use of the available resources, in particular by providing platforms for scientific exchange and the training of the next generation. At the same time, it is important to increase the work force and to strengthen collaborations and accessibility in the area of high-performance computing.

The nuclear theory survey discussed at the 100th NuPECC meeting in Vienna (http://nupecc.org/snt/meissner_sep21.pdf) clearly showed that there is a strong theory community in Europe with quite a number of early-career researchers. This observation is also reflected in the sizeable number of ERC grants in the last few years. Also, new collaborations were formed with either European leadership or strong EU involvement. These are LENPIC (Low Energy Nuclear Physics International Collaboration, https://www.lenpic.org) and NLEFT (Nuclear Lattice Effective Field Theory). Both collaborations have access to and make use of the leading supercomputing facilities in Europe. Well-established European(led) lattice QCD collaborations, such as ALPHA, BMWc, CLS, ETMC, FASTSUM, HOTQCD, QCDSF and UKQCD, rely on ample access to high-performance computing facilities, awarded via competitive calls.

With the emergence of a common European Research Area (ERA) and growing international cooperation, the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), as a highly successful and unique centre for nuclear theory, faces new opportunities and challenges. The significant European and global investments in accelerator centers and other experimental facilities require coordinated theoretical efforts which are well served by ECT*. Given its past success and the high international visibility, continued operation and financial stability need to be ensured.

ECT* is a unique centre in Europe bringing together the scientific community in theoretical nuclear physics and related areas, in the broadest possible sense. It typically runs 22 week-long workshops per year as well as a Doctoral Training Programme (3-4 weeks) and TALENT School (2 weeks, once every two years). The programme is determined by the Scientific Board, following suggestions by the scientific community. The number of visitors is around 800 annually. During the pandemic, ECT* made a successful switch to online delivery and adapted the facilities for hybrid meetings. It is expected that the post-pandemic meetings will remain hybrid, widening participation. It is envisioned that the Centre will embrace new related areas including quantum technology, artificial intelligence, and machine learning, while staying firmly rooted in nuclear physics. This will provide opportunities for networking and leadership development across the areas, linking researchers in nuclear physics with those in AI and quantum information, ensuring the nuclear physics community will continue to be at the forefront of research in the coming decade. New opportunities for funding should be identified building on this broader remit.

Nuclear theory is a significant driving force in the utilization of high-performance computing facilities at the national and European level. The planning of future high-performance installations is recognized as being of strategic importance for Europe. Being ready to exploit new computational capabilities efficiently in an early stage will be mandatory for the international competitiveness of European nuclear theory.

Exascale computing is the forefront of HPC. The first such machine in Europe will be installed at Forschungszentrum Jülich starting 2022. A number of nuclear theory groups are directly involved in this project, working on the required software to cope with this completely new architecture. Recently, artificial intelligence (AI) and machine learning, as well as quantum computing, have started to play a more prominent role across fundamental and applied sciences. It is essential for nuclear physics to embrace these new directions, as it is expected that they will play an increasing role in scientific research broadly.

Moreover, specific difficult issues arising in nuclear physics set particularly challenging questions for the quantum and AI communities and hence offer the possibility of interdisciplinary collaboration. Training the next generation in AI and quantum computing contributes to the skills development agenda, providing economical and societal impact beyond the research area itself.