Nuclear physics and the European Particle Physics Strategy Update 2018

NuPECC Working Group
A. Bracco, J.J. Gaardhøje, M. Guidal, B. Sharkov, H. Ströher, J. Wambach, E. Widmann*

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Abstract

This document provides input to the update of the European Strategy for Particle Physics in fields that are related to Nuclear Physics as described in the NuPECC Long Range Plan 2017.

Nuclear Physics European Collaboration Committee
www.nupecc.org

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*email: eberhard.widmann@oeaw.ac.at

1 Introduction

The nuclear physics community has agreed on its priorities in the NuPECC Long Range Plan (LRP) [1] compiled in 2017, in which the building and usage of dedicated accelerator facilities, in particular FAIR and Spiral-2 are emphasised. There is a large number of smaller facilities both in use and under construction, which are detailed in the following. Other facilities like ALICE, ISOLDE, and AD/ELENA are located at CERN. Applications derived from basic nuclear physics research have a large impact on many aspects of everyday life. Society benefits from the large investments done in basic nuclear physics research in areas as diverse as nuclear medicine, energy, nuclear stewardship and security. There is thus a close relationship between particle and nuclear physics, both from the physics point of view and research infrastructures.

The publication of LRPs every every 5–6 years is at the core of NuPECC's task to coordinate nuclear physics activities in Europe. The LRP outlines the perspectives of nuclear physics in the next decade and provides recommendations to funding agencies which activities and developments to support. In the current document we point out topics that are of common interest of the particle physics community for consideration in the upgrade of the European Strategy for Particle Physics (ESPP).

The document follows the structure of the NuPECC LRP focusing on recommendations from the 2017 version, including some updates where appropriate. The biggest overlap is observed in hadron physics 2.1, heavy ion collisions 2.2, and the many low-energy precision experiments that test the Standard Model of particle physics 2.5.

2 Nuclear Physics priorities form the NuPECC Long Range Plan 2017

2.1 Hadron physics

2.1.1 Summary of the Long Range Plan

Hadron physics is concerned with the study of the underlying structure and interactions of nuclear matter at the most fundamental level, that of quarks and gluons. Ultimately, the very existence of nuclei is due to the interactions of colour charged quarks and gluons, which are described by the theory of Quantum Chromo Dynamics (QCD). QCD is one of the pillars of the Standard Model (SM) of particle physics. While QCD is well tested at high energies, where the strong coupling constant is sufficiently small for perturbation theory to apply, it becomes a strongly coupled theory in the low energy regime where many aspects await a better understanding. Recent advancement in theory and experiment has allowed the field to enter into the precision domain.

Another topic relevant in the context of ESPP are searches for physics beyond the Standard Model of particle physics like precision electron scattering, charged particle electric dipole moments in storage rings, and the muon $g-2$ which are listed in sec. 2.5.

Experiments that test QCD use various probes to investigate different aspects of hadron spectroscopy, hadron structure and hadron dynamics. These experiments explore both the non-perturbative and perturbative regimes. Not one single facility or experiment can answer the big questions of the field, resulting in the existence of many facilities and in experiments located at particle physics laboratories. The most important upcoming facility is **PANDA@FAIR**, existing facilities that should continue to be fully exploited are in Europe **CERN (LHCb, COMPASS, ALICE), GSI (HADES)** and in future **CBM@FAIR** and **NICA**, and the non-European facilities **JLab** and IHEP. Smaller scale facilities of importance to hadron physics are **DAϕNE, ELSA, MAMI** and, in the near future, **MESA**. **Theory and computing** (cf. sec. 2.7.1) are of crucial importance to achieve the goals in this field.

2.1.2 New developments

The activities of the European hadron physics community will in future be supported by the project **Strong2020**, which was recently approved as a Integrating Activitiy for Advanced Communities within the European program Horizon 2020.

Fixed targets A fixed-target physics program with TeV beams (generically called AFTER@LHC) is proposed at CERN. Making use of the high luminosities reachable with fixed targets (which can be polarized) and allowing one to reach new rapidity domains and unexplored kinematics, such a program can serve the hadronic and quark-gluon plasma physics communities, with shared interests with the particle physics community.

Spin Physics Detector (SPD) at NICA. Measurements of asymmetries in the lepton pair (Drell-Yan) production in collisions of non-polarized, longitudinally and transversally polarized protons and deuterons beams are suggested to be performed at the collider NICA of the JINR using the dedicated Spin Physics Detector (SPD). These measurements can provide an access to all leading twist collinear and Transverse-Momentum Dependent distribution functions of quarks and anti- quarks in nucleons. The measurements of asymmetries in production of J/ψ and direct photons, which supply complimentary information on the nucleon structure, will be performed simultaneously with Drell-Yan data using dedicated triggers. The set of these measurements permits to tests the quark-parton model of nucleons at the QCD twist-2 level with minimal systematic errors.

EIC The Electron-Ion Collider (EIC) currently considered in the US (JLab or BNL) is a very attractive facility with a large European community. EIC aims at colliding, for the first time, spin-polarized beams of electrons and light ions, with center-of-mass energies in the range of 20 to 140 GeV and a luminosity of 10^{34} cm^{-2} s^{-1}. The scientific motivation is to study issues at the intersection of nuclear and particle physics such as the origin of the saturation of gluon densities, the evolution of partonic structure functions between free nucleons and nucleons within a nucleus, the propagation of colour charges through nuclear matter and hadronisation, the quark-gluon origin of the nuclear force, etc. From physics issues to detector techniques and R&D, there are many common and mutual interests in the EIC related to the particle and nuclear physics communities, which shall motivate strong collaboration, cooperation and involvements of both fields.

2.2 Properties of strongly interacting matter

2.2.1 Summary of the Long Range Plan

It is one of the central challenges of modern day physics to establish, understand from experiment, and be able to calculate from basic theory, the phase diagram of nuclear matter including the transitions between the various phases and the relevant equations of state. The details of the diagram are entirely governed by the strong force, whose details are still to be unravelled, although decisive progress has been made in the last decade. The (still) exotic phase diagram of nuclear matter has its parallel in the more commonly known diagram of the phases of ordinary matter (e.g. H_2O), which is governed by electromagnetic forces and is decisive for life. Some of the crucial questions are: 1) What are the fundamental properties of strongly interacting matter as a function of temperature and density? 2) How do hadrons acquire their mass and how is the mass modified by the medium they move in? 3) What are the collective and transport properties of the Quark Gluon Plasma (QGP)? 4) What is the unified description of QGP formation in the collisions, from light systems to heavy nuclei? 5) Is the Color Glass Condensate the appropriate initial condition for hadrons? 6) Are there color superconductors and highly dense gluonic objects in Nature? The NUPECC Long Range Plan 2017 identified the following main priorities for the 10 year horizon:

a) Vigorous continuation of the heavy-ion (HI) program at the LHC with Runs 3 and 4, including the planned detector upgrades of **ALICE**;

b) Continuation of the ongoing programs: **HADES** at SIS-18, **NA61** at the SPS at intermediate energies;

c) Timely construction of **SIS-100** at FAIR and the realization of the **CBM** experiment to investigate nuclear matter at high baryonic density;

d) Support of a future accelerator upgrade at FAIR;

e) Completion of the **BM@N** experiment at JINR, and construction of the **NICA** facility and the associated **MPD** experiment;

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

At LHC, the ongoing upgrade of the dedicated HI ALICE detector to high collision rate operation will open up for entirely new detailed studies of strongly interacting matter, complemented by the broader HI program at the other LHC detectors (ATLAS, CMS and LHCb).

2.2.2 New developments

On the longer timescale, novel technology based on pixel sensors will enable the construction of an all-silicon tracker with unprecedented low mass made of wafer-scale ultra-thin (0.05% X_0 per layer) and flexible Si-pixel detectors. Such a detector would open up a new field of studies of very low transverse momentum lepton-pairs, photons and hadrons at the LHC , to measure the primordial QGP electromagnetic radiation and multiply heavy flavored baryons emitted by the QGP produced in nuclear collisions, providing key information for the understanding of the emergent properties of QCD matter. Forward calorimetry extensions would add new directions in low-x physics and tests of Color Glass Condensate predictions. Many physics observables, currently beyond reach, will benefit from high intensity running with lighter beam species (e.g. Ar or Kr) beyond the currently approved program (after LHC run 4).

2.3 Nuclear structure and reaction dynamics

2.3.1 Summary of the Long Range Plan

The strong interaction described by quantum chromodynamics is responsible for binding neutrons and protons into nuclei and for the many facets of nuclear structure and reaction physics. Combined with the electroweak interaction, it determines the properties of all nuclei in a similar way as quantum electrodynamics shapes the periodic table of elements. While the latter is well understood, it is still unclear how the nuclear chart emerges from the underlying strong interactions. This requires extensive experimental information which is at the basis of a unified description of all nuclei with theories of strong interactions at low energies and with advanced few- and many-body methods for nuclear structure and reactions. In this very vital sub-field of nuclear physics a number of key questions have to be addressed, the overarching ones being the search of the limits of stability, including superheavy elements, and how nuclear structure evolves across the nuclear landscape and manifests features that are enhanced far from stability. Nuclear structure features, particularly in neutron rich matter, have very important implications in the nuclear equation of state and thus the interest in their investigations is also dictated by the need to contribute to the modeling of neutron stars.

The experimental challenge which is being pursued is to measure the different observables for nuclei far from stability in their ground and excited states and in their beta and alpha decays. This requires an arsenal of beam types and a wide range of energies from few MeV to GeV. The research in this field is thus distributed over **several facilities in Europe** which are organized within the European Integrated Activity project **ENSAR2** giving strength to the science, connecting the ongoing programs, and supporting R&D for the newer larger facilities under construction. For the electromagnetic nuclear properties **ELI-NP** will provide unique contributions, while for the synthesis of superheavy nuclei the dedicated factory at **JINR** in Dubna is going to give outstanding unique results. Among the experiments addressing this problem there are nuclear reactions at the storage ring of GSI.

The future in this field is well defined at the **NUSTAR** pillar of FAIR (including large-size instruments such as the **SuperFRS** and **R3B**), producing radioactive beams in-flight with energies up to GeV/u and at the ISOL facilities **SPES** (at LNL), **SPIRAL2** (at GANIL), and **ISOLDE** (at CERN) producing low energy beams. SPES will concentrate on nuclei produced as fission fragments, SPIRAL2 will have the highest intensity and will provide a new generation of radioactive ion beams also on the proton rich side. The ISOLDE facility uses as primary beam the high energy protons of the PS accelerator and with more than 50 years of experience is a reference for scientific and technical results. The **AGATA** array for gamma spectroscopy has been and will be installed at the above facilities.

2.3.2 New developments

As described in a specific contribution by ISOLDE to the ESPP, in the next years this facility is planning upgrades in intensity, in the number of beam lines and also the construction of a storage ring, unique for an ISOL facility. In addition to these facilities, which are in the first recommendations of the NupECC LRP2017, the recent approval of the first phase of the **MYRRHA** project, opens new opportunities for decay studies of non accelerated beams at the planned ISOL station. Last but not least it has be pointed out that presently an effort is made to construct a **distributed facility** among the ISOL infrastructures (with SPES, SPIRAL2 and ISOLDE as main pillars) to be possibly recognized by ESFRI. The program at these distributed facilities is complementary to that at FAIR and altogether FAIR and the ISOL facilities will allow exciting research in the future for more than one decade.

2.4 Nuclear astrophysics

The world around us is intimately linked with the properties and reactions of atomic nuclei. From the lives and deaths of stars, to the evolution of the Galaxy, it is nuclear physics that has shaped the Universe, linking processes that operate at femtometer scales to structures that stretch across thousands of light years. Nuclear astrophysics brings together different scientific disciplines to answer some of the key questions about the Universe. The challenge of understanding the origin and evolution of the chemical elements, and the role of nuclear physics in the lives and deaths of stars, requires state-of-the-art experimental, theoretical and observational capabilities. Nature has supplied the Earth with about 300 stable as well as long-lived radioactive isotopes that we can study in the laboratory. However, a much greater variety of (mostly unstable) isotopes is produced during stellar explosions and, as recently found, also neutron star mergers that are one of the sources of gravitational waves. One of the multi-messenger signals produced by neutron star mergers is the production of heavy nuclei belonging to the third peak of the nucleosynthesis r-process. Nuclei forming this third peak are not yet investigated and there is clearly an urgency to learn about them. **FAIR** with the **NUSTAR** pillar (in the top priorities in the NuPECC LRP) will give access to such investigations and will have a worldwide leadership because of the high beam energies and intensities that will be available.

Due to the great diversity and strong interdisciplinary character of the field, nuclear astrophysics requires a wide range of experimental facilities, from major international laboratories to smaller university-based centres. The small scale underground facilities **LUNA** and **Felsenkeller** with the new multi-MV accelerator and associated infrastructure, will allow for access to a new range of nuclear reactions for the nucleosynthesis of light elements and energy production in stars. In addition, many large-scale European nuclear physics facilities, **GSI/FAIR** and the **ISOL** facilities ISOLDE, GANIL/SPRAL2, SPES at LNL, maintain and/or are planning a strong research programme in nuclear astrophysics and will make important contributions to our understanding of explosive astrophysical environments, and of the nuclear Equation of State (EoS) through the properties of neutron rich matter. At the facility **ELI-NP** the unique program to measure reactions in the plasma using the available Laser system will be carried out.

It is very clear nuclear physics is crucial for our understanding of the evolution and explosion of stars but on the other hands the nuclear properties relevant for the description of astrophysical processes depend on the environmental conditions. Nuclear theory is fundamental to connect experimental data with the finite temperature and high density conditions in the stellar plasma. Advances in the description of nuclear interactions based on the symmetries of quantum chromodynamics, together with novel many-body techniques, allow for parameter-free calculations of reactions relevant for stellar burning. Microscopic approaches from light toward heavy nuclei will allow for theoretical predictions relevant for the description of explosive scenarios.

2.5 Symmetries and fundamental interactions

2.5.1 Summary of the Long Range Plan

Nuclear Physics has played a major role in finding and establishing the laws which govern Nature at the most fundamental level. Among the most notable examples are the discoveries of parity (P) and charge-parity (CP) violations, which triggered intense research on symmetry violations in general.

Today, sophisticated technologies from various fields are employed to prepare the fundamental systems for symmetry investigations. They involve the use of low-energy particles, ultracold atoms, ions and molecules, novel sensors and radiation detectors and the analysis of complex data sets to extract the underlying information. At the same time the most advanced theoretical and computational techniques are developed to perform ever more stringent comparisons between theory and observation, and to establish discrepancies.

Despite the success of the Standard Model of Elementary Particle Physics (SM), various observations, such as, e.g., the likely existence of Dark Matter (DM) and the Baryon Asymmetry of the Universe (BAU), point to the need for its extensions: these call for baryon number (B) violation, connected or not to lepton number L violation, and for additional CP violation. Symmetry test broadly can be arranged into (i) precision determination of SM parameters and (ii) searches for physics beyond the SM. They involve the full spectrum of particles from neutrinos and charged leptons to hadrons and stable as well as radioactive ions and molecules. Essential facilities in Europe are the **AD & ELENA** at CERN, cold and ultra-cold neutron facilities **ILL, FRM-II** and **ESS**, the radioactive beam facilities **GSI/FAIR, ISOLDE, GANIL, LNL**, and **JYFL**. At **GSI/FAIR** NUSTAR and SPARC will exploit highly-charged (exotic) ions in combination with various storage and trapping facilities. **PSI** delivers the world highest intensities of pions and muons as well as ultra-cold neutrons, electron scattering facilities like **MESA** (Mainz) study the properties of the proton, **DAΦNE** provides low-energy kaons for exotic atom studies, and the underground laboratories **LNGS, Modane** and **Canfranc** provide ideal conditions for background sensitive experiments.

2.5.2 New Initiatives

Search for charged-particle Electric Dipole Moments (EDM) in storage rings. The search for EDMs of proton, deuteron and other light ions can be pursued in dedicated precision storage rings. Using polarized beams, the interaction of an EDM with a radial electric field leads to a torque, which very slowly rotates the spin vector. This miniscule spin precession can be observed by precision polarimetry and must be separated from the much larger effects due to the magnetic moment. The techniques to achieve this are: (i) operation at the magic momentum, when the spin always points in the momentum direction, and (ii) clock-wise (CW) and counter- clock-wise (CCW) beams, simultaneously circulating in the ring. The strategy of the community (JEDI, CPEDM collaborations) is to (i) perform a precursor experiment at COSY as a proof-of-concept, (ii) design and build a prototype ring to obtain a proof-of-principle for the key-technologies, such as storage and spin coherence time of CW and CCW beams, and (iii) finally build an all-electric CW-CCW precision storage ring for protons at magic momentum to achieve a sensitivity of the order of 10^{-29} e.cm, thus pushing the EDM limit deep into previously uncharted territory. It should also be mentioned that EDM rings can be used to search for axions as possible Dark Matter candidates over a wide mass range (10^{-6} to approximately 10^{-22} eV).

2.6 Applications and social benefits

Applications derived from basic Nuclear Physics Research have a large impact on many aspects of everyday life. Society benefits from the large investments done in basic Nuclear Physics research in areas as diverse as nuclear medicine, energy, nuclear stewardship and security. Recent achievements in **particle- and radio-therapy** within the new paradigm of a theranostic approach, developed as an extension of the successful hadron therapy treatment at GSI, are but some of the most striking examples of the benefits from nuclear physics. Improvements in nuclear applications were obtained thanks to an increase of the basic knowledge on nuclear structure and decay, nuclear reactions and nuclear system properties but also thanks to the developments in related technologies, such as **accelerator science**, **instrumentation** and **high-performance computing**. The nuclear physics community continues to build on its strong track record to answer fundamental societal needs specifically on **energy, health** and **security**. This has led to a new transverse discipline of Applied nuclear physics research. Reliable, up-to-date and well-structured **data libraries** are indispensable both for Applied and Fundamental nuclear physics research. The ability to develop and maintain a high level of expertise in the area of nuclear data to meet the data needs of a continuously developing European nuclear physics landscape is a key issue.

Nuclear application activities are carried out in all European laboratories dealing with nuclear physics. Important research developments are integral part of the programmes of upcoming facilities or under constructions (such as **FAIR, NICA, SPIRAL2, SPES**, and in particular **ELI-NP** has a large component in its program devoted to applications using lasers). The research for the production of radioisotopes for medical applications is one of the activities at facilities producing radioactive beams. In this context it is very important to underline the **MEDICIS** facility at CERN, which was built to exploit for medical applications the many unique developments carried out at ISOLDE. The MEDICIS facility is ready to pave the way to very interesting research for medicine in the future. It should be noted that the facility MYRRHA will also contribute to the same research field as covered by MEDICIS, but using higher beam intensities and lower energies and thus developing different technologies. For **MYRRHA** the application part is well inserted in the first phase of the project and again the collaboration with the other facilities (including also the **ILL** reactor) is crucial to be successful in the planned ambitious developments.

2.7 Other topics

2.7.1 Theory and computing

Nuclear theory is making major conceptual and computational advances that address the fundamental questions in the strong-interaction sector of the Standard Model. These concern the high-temperature and high-density behaviour of matter as encountered in cosmological settings and the emergence of hadrons and nuclei from the complex dynamics of quantum chromodynamics (QCD). They are driven by discoveries such as the detection of perhaps the most exotic state of matter, the quark-gluon plasma, which is believed to have existed in the very first moments of the Universe. The recent detection of gravitational waves from a neutron-star merger focusses attention on the equation of state at high baryon densities, which is still not well understood. High-precision measurements of the quark structure of the nucleon are challenging existing theoretical understanding. Nuclei constitute a unique laboratory for a variety of investigations in fundamental symmetries, which in many cases are complemetary to particle physics. These include searches for dark matter, neutrinoless double-beta decay and others that require strong guidance from nuclear theory.

With continued major conceptional and computational advances, nuclear theory plays a crucial role in shaping existing experimental programs in Europe and provides guidance to new initiatives in nuclear physics. 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 of nuclear theorists.

Accompanying the experimental developments, qualitative changes in the theoretical understanding of strong-interaction matter have taken place through significant improvement in numerical algorithms and high-performance computing. Lattice simulations of the QCD thermodynamics have entered the precision era, now providing stringent predictions of the equation of state near the quark-hadron transition for moderate baryon chemical potentials. Similarly, lattice studies of hadron structure and spectroscopy have led to major advances on a quantitative level. Lattice calculations of hadronic contributions to precision observables are indispensable for exploring the limits of the Standard Model. A combination of techniques has also provided links between lattice QCD calculations of nuclear few-body systems and ab initio methods for the solution of the nuclear many-body problem. Effective field theories rooted in QCD attempt at building a bridge through direct lattice simulations of the properties of light nuclei or to convert the results of lattice QCD into input Hamiltonians that can be used in ab initio many-body methods. The theoretical tools have matured such that they begin to span the strong-interaction landscape from the elementary constituents, quarks and gluons, as the building blocks for the computation of hadrons and nuclei to the computation of the equation of state for infinite nuclear matter and neutron star matter. In all areas of theoretical nuclear physics algorithmic and computational advances thus hold promise for breakthroughs in predictive power including proper error estimates. Recent developments in quantum computing platforms and algorithms hold the potential for breakthrough solutions for the fermion sign problem and the evolution of nuclear systems in real time.

Nuclear theory is a significant driving force in the utilization of high-performance computing facilities and the exploration of rapidly growing opportunities in quantum computing at the national and European level. The planning of future compute installations and the exploration of quantum computation possibilities is recognized as being of strategic importance for Europe. Being ready to exploit new computational concepts and capabilities will be mandatory for the competitiveness of European nuclear theory.

References

[1] NuPECC Long Range Plan 2017, *Perspectives in Nuclear Physics*, http://www.nupecc.org/lrp2016/Documents/lrp2017.pdf