THE NUPECC LONG RANGE PLAN 2017: PERSPECTIVES IN NUCLEAR PHYSICS

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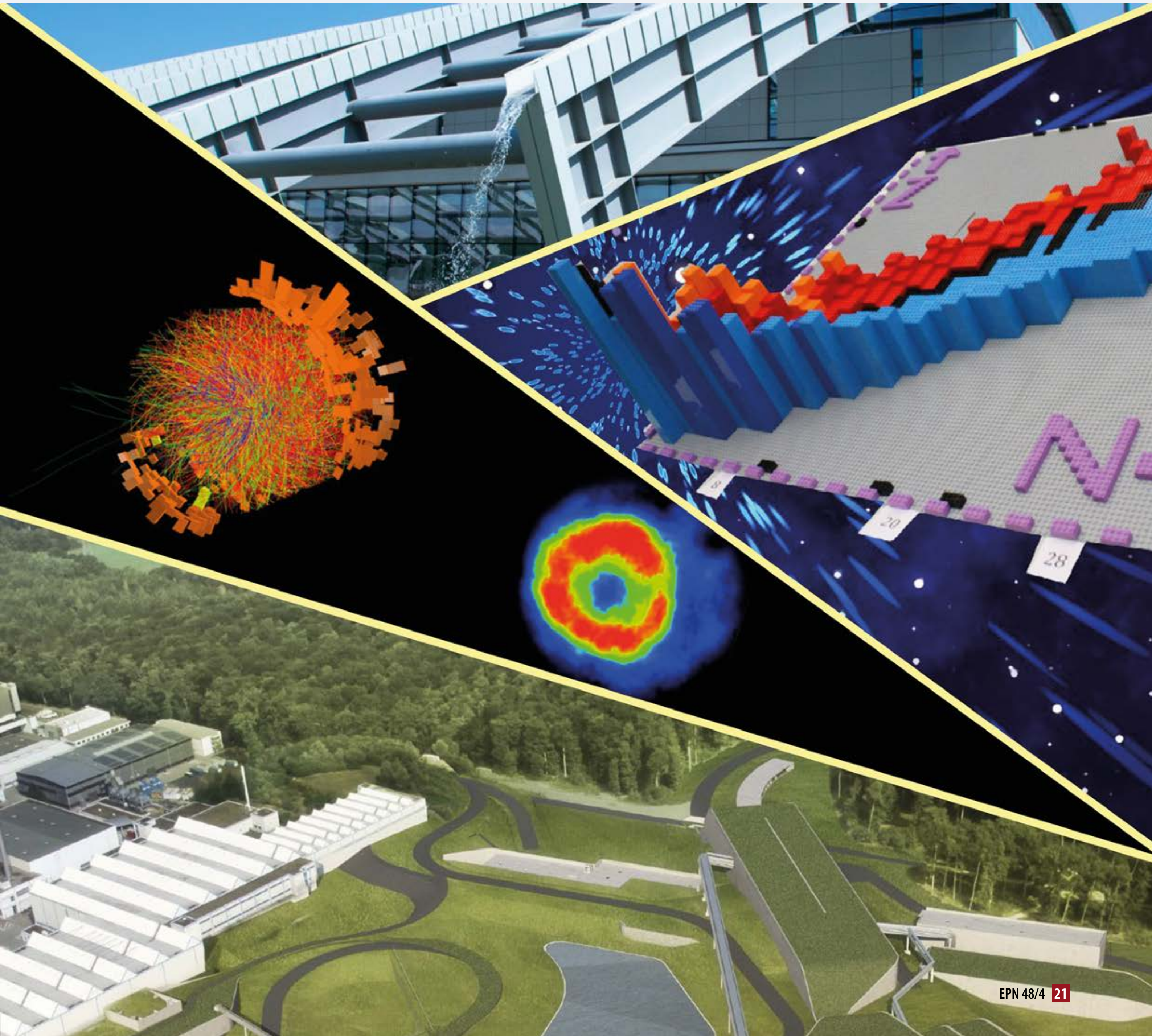
The Nuclear Physics European Collaboration Committee (NuPECC) is an independent Committee associated to European Science Foundation (ESF). Its mission is "to provide advice and make recommendations on the development, organisation, and support of European nuclear research and of particular projects". The delivery of long range plans represents thus the core of the NuPECC's activities. In the past four long-range plans (LRPs) were issued in 1991, 1997, 2004 and 2010.

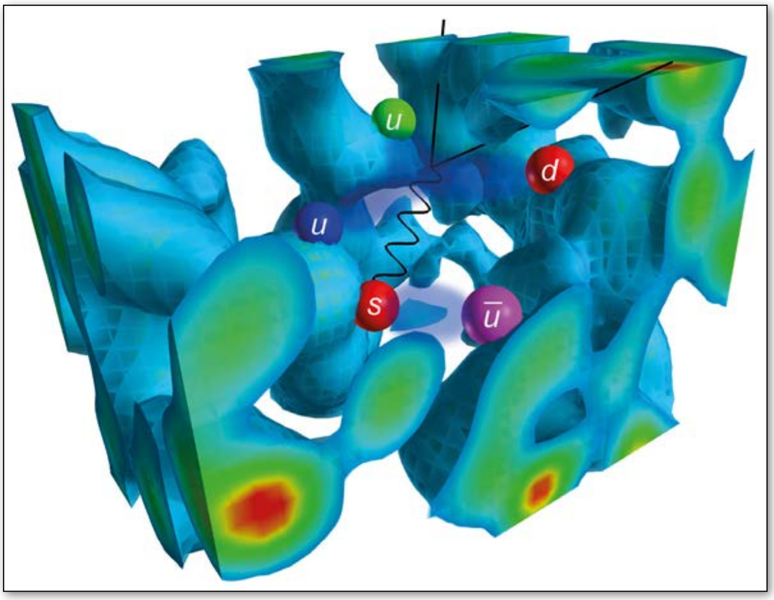


On the 19th of June 2017 the "Long Range Plan for Nuclear Research in Europe" prepared by NuPECC was released after approximately 20 months of work for its preparation. This document comes 7 years after the previous Long Range Plan (LRP) . During these 7 years substantial progress was made in the different areas of Nuclear physics (schematically shown in Fig.1). Although NuPECC's recommendations in previous LRP's were decisive for approval of facilities (from the smallest ones as *e.g.* LUNA at LNGS to the largest international facility FAIR) it turned out that their full construction is requiring in some cases additional time. Therefore when it was decided to build this new LRP it was clear that several previous plans need to be updated and consolidated according to the present conditions and to the new projects.

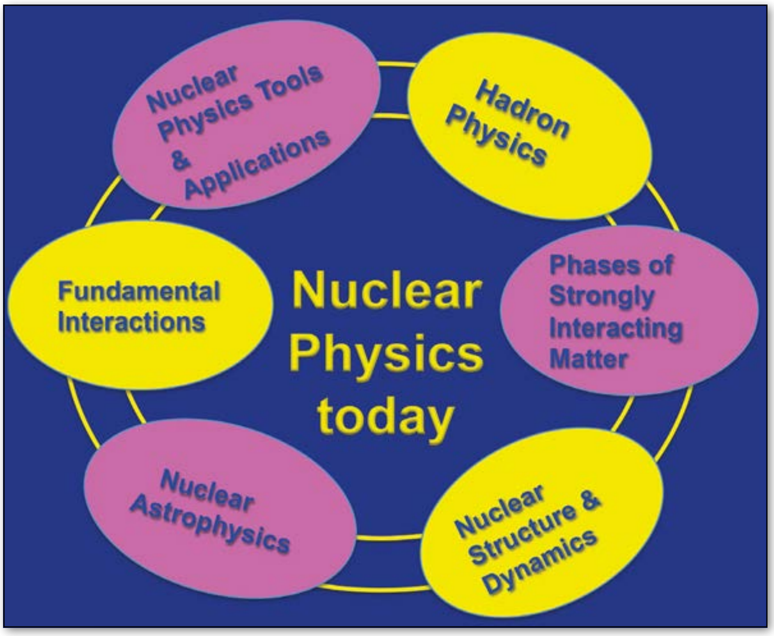
As in the case of the previous editions, this LRP is expected to play the role of an important reference and guide for the field for at least the next 6 years.

Similar to several countries in the world beyond the European boundaries, today Nuclear Physics is defined as a field including different research domains sharing the difficult but stimulating task to study nuclear matter in all its forms and of exploring their possible applications. The knowledge of the properties of nuclear matter is essential if one wants to address several key issues for the understanding of the different stages concerning the origin and the evolution of the universe.

The overarching goal of nuclear physics is to unravel the fundamental properties of nuclei from their building blocks, protons and neutrons, and ultimately to determine the emergent complexity in the realm of the strong interaction from the underlying quark and gluon degrees of freedom of Quantum Chromodynamics (QCD). This requires detailed knowledge of the structure of hadrons, the nature of the residual forces between nucleons resulting from their constituents and the limits of the existence of bound nuclei and ultimately of hadrons themselves. A thorough understanding is vital for the complex structure of nuclei, nuclear reactions, and the properties of strong-interaction matter under extreme conditions in astrophysical settings and in the laboratory. Nuclei also constitute a unique laboratory for a variety of investigations of fundamental physics, which in many cases are complementary to particle physics.



▲ FIG 2: Pictorial view of a QCD calculation for the structure of the particle Lambda 1405 (from CSSM, University of Adelaide).



▼ FIG 1: Pictorial illustration of the different sub-fields of Nuclear Physics.

Substantial experimental and theoretical efforts are being made world-wide to address the central questions of nuclear physics, which include:

- How is mass generated in QCD and what are the static and dynamical properties of hadrons?
- How does the strong force between nucleons emerge from the underlying quark-gluon structure?
- How does the complexity of nuclear structure arise from the interaction between nucleons?
- What are the limits of nuclear stability?
- How and where in the universe are the chemical elements produced?
- What are the properties of nuclei and strong-interaction matter as encountered shortly after the Big Bang, in catastrophic cosmic events, and in compact stellar objects?

These fascinating topics in basic science require concerted efforts in the development of new and increasingly sophisticated tools such as accelerators and detectors. It is important to emphasise that knowledge and technical progress in basic, curiosity-driven nuclear physics has significant societal benefits including the training of a highly skilled workforce and broad applications in industry, medicine, and security.

The research driven by the goal of answering to these important questions is organized in six different subfields of nuclear physics defined by NuPECC as: Hadron Physics, Properties of Strongly Interacting Matter (at extreme temperatures and density), Nuclear Structure and Dynamics, Nuclear Astrophysics, Symmetries and Fundamental Interaction as well as Applications and Societal Benefits.

Understanding the physics of hadrons requires a large variety of complementary experiments and theoretical tools (see *e.g.* Fig. 2). In experiments, electromagnetic and hadronic probes can be used to study various aspects of hadron structure, spectroscopy and dynamics at different energy scales, at existing and future facilities.

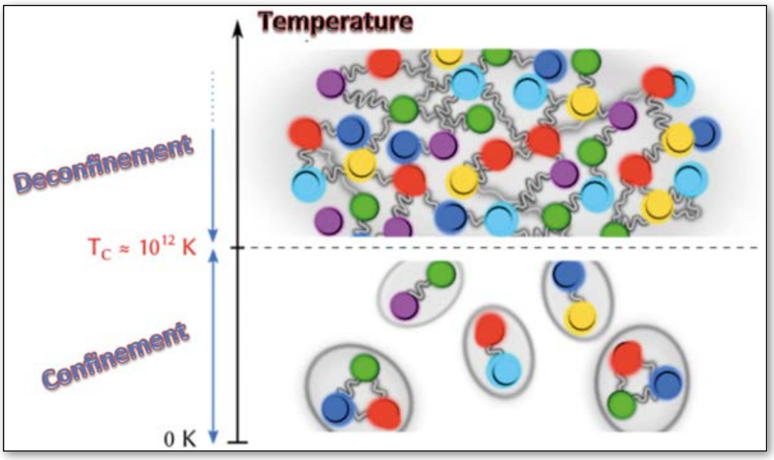
The transition between the primordial quark-gluon plasma (QGP) from big bang and the hadron formation has, as far as we know, not left any imprint that is visible in present-day astronomical observations (see *e.g.* Fig. 3). However, the energy or baryon densities necessary to form the QGP may be recreated in the laboratory (such as in ALICE at CERN) via heavy ion collisions at sufficiently high energies in the nuclear dimension.

Presently is still unclear how the nuclear chart emerges from the underlying strong interactions. This requires the development of a unified description of all nuclei based on systematic theories of strong interactions at low energies and experiments providing different observables for nuclear excitations and decays particularly for radioactive nuclei, far from stability (see *e.g.* Fig. 4).

Many, if not all, nuclear properties of stable and unstable nuclei and of nuclear reactions are relevant for the description of astrophysical processes such as stellar burning, the evolution and explosion of stars, the chemical evolution of the Galaxy and its assembly history (see *e.g.* Fig. 5).

Specific very high precision measurements in stable and unstable nuclei (including nucleons and antinuclei) allow tests of our understanding of nature and of symmetries that are complementary to experiments at the highest energies (see *e.g.* Fig. 6). In some cases they offer higher sensitivities to new effects beyond the Standard Model (SM) of particle physics. This research is and will be performed in the future at several laboratories.

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 are in areas as diverse as nuclear medicine, energy, nuclear stewardship and security. Improvements in nuclear applications are 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 (see. *e.g.* Fig. 7), instrumentation and high-performance computing.

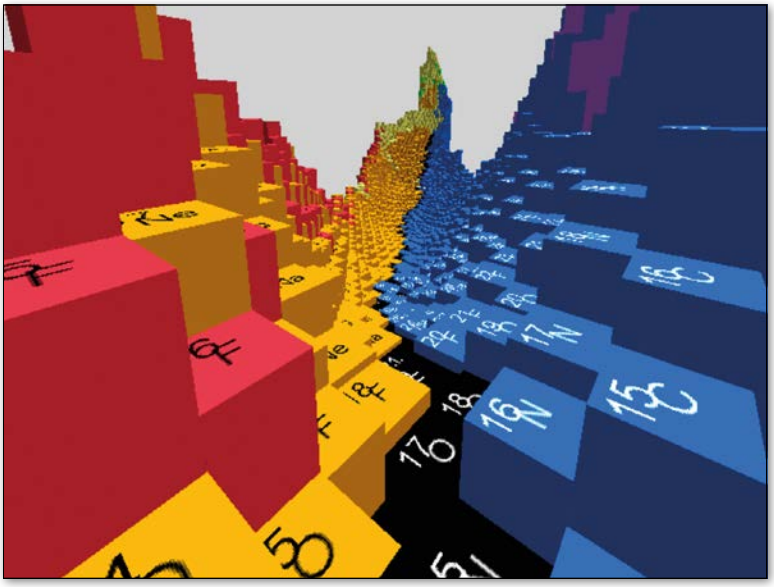


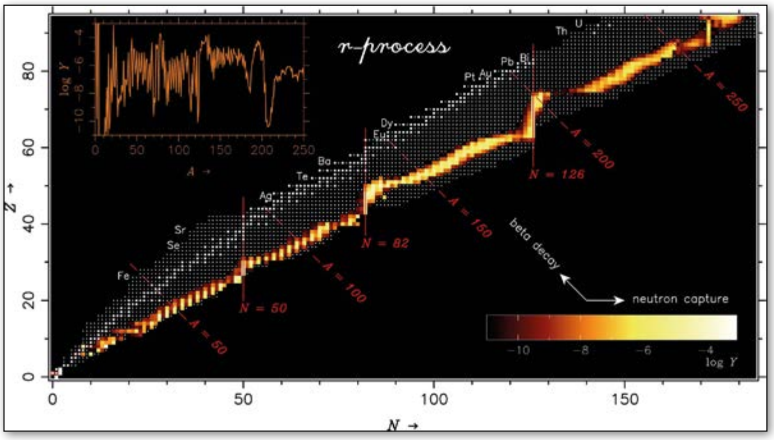
▲ **FIG 3:** Schematic illustration of the quark confinement in baryons and mesons and, at high temperature, the quark deconfinements.

The preparation of NuPECC Long Range plans is a bottom up process. It requires dedicated efforts from many physicists of the nuclear physics community. The contributors were organized in six working groups each corresponding to one of the subfields given above and led by two Conveners and three Liaison Members of NuPECC. The Working Groups were given the charge to delineate the most exciting physics in their subfields, to highlight recent achievements, and future perspectives. Draft reports from the Working Groups were presented and discussed in internal workshops and at NuPECC Meetings.

A Town Meeting to discuss the NuPECC LRP was held at the "darmstadtium" in Darmstadt, from January 11 – 13, 2017. The Town Meeting was attended by almost 300 participants, including many young scientists. The programme contained, in addition to the presentation of the Working Groups, sessions on future facilities: FAIR, the ISOL facilities (SPIRAL2, ISOLDE and SPES), ELI-NP in Bucharest, NICA and the Dubna Superheavy Element Factory, as well as a presentation of CERN from its scientific director. For the international context the overview given by the Chairs of of the two committees NSAC (USA) (Nuclear Science Advisory Committee of

▼ **FIG 4:** Illustration of the valley of stability within the nuclear chart. Stable nuclei (black) are the most tightly bound, whereas nuclei with proton or neutron excess are unstable (picture from CSNSM Orsay).





▲ FIG 5: Calculated abundance distribution of nuclides during r-process nucleosynthesis (*Astrophys. J.* **606** (2004)1057).

the Department of Energy) and ANPhA (Asia) (Asian Nuclear Physics Association) were much appreciated. The Town Meeting was concluded by a general discussion.

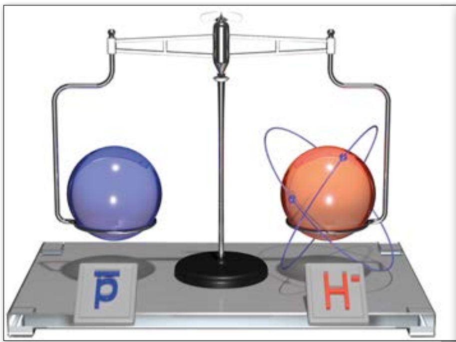
The recommendations with their wording were extensively discussed, not only at the town meeting but also later on at the NuPECC meetings. It is not possible here, due to space limits, to quote them directly in their complete form and thus the reader is invited to read our webpage http://www.nupecc.org/pub/lrp2017.pdf.

In short, the recommendation section includes the following : i) a recommendation for the construction and operation of the flagship facility FAIR with its experimental programme at the four scientific pillars APPA (fundamental interaction and applied sciences), CBM (compressed barionic matters with heavy ion reactions), NUSTAR (nuclear structure and astrophysics with radioactive beams) and PANDA (hadron physics with antiprotons); ii) support for construction, augmentation and exploitation of world leading ISOL facilities for low energy radioactive beam in Europe (SPIRAL2 (France), HIE-ISOLDE (CERN), and SPES (Italy)); iii) the exploitation of the existing and emerging facilities, the latter being ELI-NP in Bucharest (providing lasers and gamma beams) and NICA in Dubna (for hadron physics and quark gluon plasma); iv) support for ALICE and the heavy-ion programme on the quark-gluon plasma at the LHC (CERN) experiments with the planned experimental upgrades; v) support to the completion of AGATA (a European array for gamma spectroscopy) in full geometry; vi) support for Nuclear Theory. In addition, the particular role of R&D for future projects, of education and training, and of small scale facilities are underlined in the recommendation section and also in the different chapters of each subtopic.

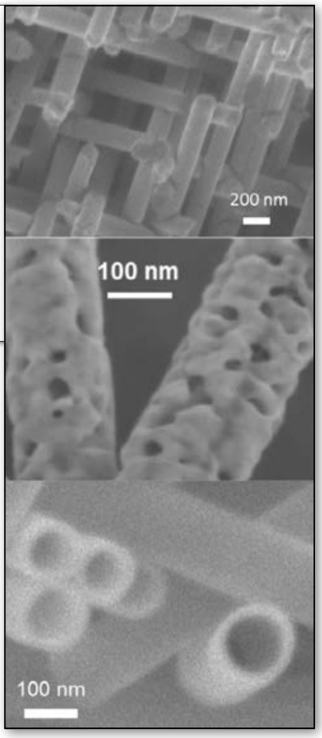
In the introduction chapter one can find special mention to the contribution received by the European Commission to the different facilities, the ones focussing on hadron physics (the last integrated activity being HP3) and the ones on nuclear structure and astrophysics (presently in the ENSAR2 integrated activity). Concerning the more general scientific context, in which the Nuclear Physics infrastructures are placed, the relation of NuPECC with ESFRI (the European Strategy Forum for Research Infrastructure) is very important and fruitful.

Last but not least, in the introduction and also in various chapters, the role of international collaborations worldwide, outside Europe (the largest fraction being in USA and Japan), is underlined, resulting in major achievements in the field. These collaborations are expected to continue and to be reinforced in the future.

The release of the long range plan was possible thanks to the work of several researchers involved directly or more indirectly in this process. Now these active players in the field are expected to further enhance the vitality of the field by using this long range plan as key tool for this purpose. Indeed, it will be very important in the next years to implement the goals outlined in the recommendations, in particular also those that go beyond the capabilities of an individual country. ■



▲ FIG 6: Illustration of the comparison of the gravitational mass of an antiproton and a proton, which was obtained by comparing the cyclotron frequency of an antiproton and a H^- ion in a Penning trap (From Georg Schneider, BASE collaboration)



▶ FIG 7: Novel ion-track technology based nanostructures such as nanowire networks (top), porous wires (center) and nanotubes (bottom) with tailored diameter, length and surface (From C. Trautmann, GSI).

About the Author

Angela Bracco is full professor in experimental physics at the Università degli Studi di Milano and is associated to INFN. Her research field is nuclear structure mainly addressed via gamma spectroscopy and using nuclear reactions with stable and radioactive ion beams. She is member of the steering committe of AGATA, the last generation detector system for gamma-ray spectroscopy, used in several European laboratories. In 2017 she was scientific associated at CERN. She chaired in 2012-2017 NuPECC the expert board for European Nuclear Science. She is in the executive committee of EPS. She also served as member and chair of several advisory and review panels for different institutions in Europe, USA and Japan.