Eur. Phys. J. Plus (2022) 137:350
https://doi.org/10.1140/epjp/s13360-022-02552-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Editorial

Editorial: re-writing nuclear physics textbooks

Recent advances in nuclear physics applications.

Nicolas Alamanos[1], **Carlos Bertulani**[2], **Angela Bonaccorso**[3,a], **Angela Bracco**[4], **David M. Brink**[5], **Giovanni Casini**[6], **Maria Agnese Ciocci**[3,7], **Valeria Rosso**[3,7], **Michele Viviani**[3]

[1] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[2] Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce TX 75429, USA
[3] INFN-Pisa, 56127 Pisa, Italy
[4] Dipartimento di Fisica, Universita' degli Studi di Milano and INFN-Milano, 20133 Milano, Italy
[5] Rudolf Peierls Centre of Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK
[6] INFN-Firenze, 50019 Sesto Fiorentino, Firenze, Italy
[7] Dipartimento di Fisica, Universita' di Pisa, 56127 Pisa, Italy

This collection of articles contains eight of the twelve lectures presented at the Summer School "Re-writing Nuclear Physics textbooks: Recent advances in nuclear physics applications" which was held at the INFN Sezione di Pisa and Department of Physics of the University of Pisa during the week 22–26 July 2019. For the missing papers, we refer the readers to the lecture slides at https://agenda.infn.it/event/17273/timetable/?view=standard or, in the case of Nick van der Meulen lecture, to the literature provided. The School followed two previous editions dedicated to "30 years with Radioactive Ion Beam Physics" and "Basic Nuclear Interactions and Their Link to Nuclear Processes in the Cosmos and on Earth" also held at the same place in Pisa in July 2015 and July 2017 whose lectures were collected in the two focus points Eur. Phys. J. Plus (2017) 132: 37 and Eur. Phys. J. Plus (2019) 134: 183, respectively.

The objective of the event was to attract and educate the best possible students introducing them to the wonders of the Nuclear Physics applications in various contexts of our modern society. We tried to convey to such students a view of the rich variety of on-going activities in the field, mainly experimental but also theoretical, so that the progress made in the last years can be developed further in the future with the help of a new generation of bright scientists.

The activities were directed toward students who were in the process of deciding what graduate studies to specialize on. Those students were selected and granted scholarships on the basis of their profit and interest in Nuclear Physics. The activity consisted of twelve lectures. Each lecture covered a topic in the field of nuclear applications rarely covered in standard basic Nuclear Physics textbooks. In order to give the activity a fully international character, and because we aimed at favoring the participation of young students, the first half day we included a few introductory lectures. Lecturers were also invited to organize and participate in afternoon tutorials in order to answer the questions by the students. During the last day, we visited the INFN-LABEC (Laboratorio di Tecniche Nucleari Applicate ai Beni Culturali) laboratory in Florence.

The format of the school was unique and original. There were about 60 participants of which 40 were undergraduate students. Such a large participation represented a great success for our community. In the following, we describe briefly the content of each lecture and we hope they will be instructive for many students and colleagues all over the world, now and for several years to come.

Introduction to modern nuclear physics by Nicolas Alamanos (CEA-SACLAY/IRFU).

The third edition of the school "Rewriting Nuclear Physics Textbooks: one step forward" was devoted to the societal impact of nuclear physics. One of the main beneficiaries in this area is medicine. From magnetic resonance imaging (MRI) to the different types of radiation used in hospitals, nuclear physics is omnipresent. The development of new radioisotope production techniques, therapy of certain cancers with ions and hadron therapy are among the subjects undergoing rapid development. Many other fields benefit from the techniques of nuclear physics: archaeometry, the non-destructive investigation of packages or containers at customs, the study of the pollution of our environment, etc. The school was completed by the presentation of some basic research topics: the contribution of cold and ultra-cold neutrons to the study of the lifetime and electric dipole moment of the neutron, the measurement of the proton charge radius via the study of muonic atoms, the investigation of the extremes of neutron richness in nuclei, and finally, the quest for traces of ^{60}Fe in sediments in order to study the history of supernova explosions in our universe. The number and quality of projects in a scientific field give a measure of its future. For nuclear physics, the number of accelerators under construction

This paper is dedicated to the memory of our colleague Shawn Bishop who gave a very lively presentation at the school. To our great regret, Shawn fell ill and passed away before he could write up his contribution.

[a] e-mail: angela.bonaccorso@df.unipi.it (corresponding author)

Published online: 16 March 2022

in the world attests to the robustness and the future of the field. In the last part of the article, the author briefly recall the specifics of nuclear physics accelerators under construction throughout the world. In the introductory presentation at the school, the author covered all of these topics by pointing out the contributions of nuclear physics. The article closely follows his presentation.

How a small accelerator can be useful for interdisciplinary applications. Part I: the study of air pollution by Franco Lucarelli (INFN-LABEC, Firenze).

There is an increasing concern in European countries about the consequences of the high levels of particulate matter (PM) in our cities, which affects human health. Aerosol also affects climate change, directly by scattering and absorption of solar radiation and indirectly by impacting on cloud dynamics processes. In environmental sciences, Nuclear Physics plays an important role through the measurement of the elemental composition of the aerosol, in particular with particle induced X-ray emission (PIXE), which is a very sensitive method for detecting trace elements. A better knowledge of the aerosol composition helps to identify its sources. It also brings valuable information for epidemiological studies or to constraint climate models. With PIXE, all the elements with $Z > 10$ are simultaneously detected in a measuring time very short ($\sim$60 sec with respect to the several minutes or hours typical of other competitive techniques); furthermore, no sample pre-treatment is necessary. This is especially important when samples with very low mass must be analyzed and therefore any contamination is dramatic (e.g., mineral aerosol in polar ice cores for paleo-climatic studies). However, a proper experimental setup must be used to exploit all PIXE capabilities. Theoretical fundamentals, a description of the experimental setup and some applications are discussed.

Nuclear Physics applied to the production of Innovative Radio-Pharmaceuticals by Andrea Fontana (INFN—Pavia) and Luciano Canton (INFN—Padova).

The article introduces the basic concepts related to radionuclide production at cyclotrons for radiopharmaceuticals applications. The main goal is to find efficient production routes of novel radiopharmaceuticals (theranostics, multimodal imaging, etc.), with special considerations about purity and yields. There is a discussion on the different reaction mechanisms (and the underlying theory) that are important for the production cross sections in the available energy regime. A survey of the most commonly used nuclear reaction codes for simulations and prediction of cross sections is given.

Study of nuclear properties with muonic atoms by Andreas Knecht (Paul Scherrer Institute, Zurich).

Muonic atoms used as laboratories for fundamental physics provide a crucial test of quantum electrodynamics, the weak interaction and the strong interaction. Muonic atom spectroscopy, i.e., the detection of the muonic X-rays emitted subsequently to the atomic capture of a negative muon, has been a technique very extensively used to determine the extent of the nuclear charge distribution. This method for determining nuclear charge radii complements the knowledge from electron scattering experiments and laser spectroscopy. Other properties such as quadrupole moments can be extracted as well. In addition to the muonic X-rays, it is also possible to study the gamma rays emitted following the capture of the muon by the nucleus. This gives access to nuclear matrix elements and is especially relevant for neutrinoless double beta decay as the momentum transfer in muon capture is high and thus very similar states can be probed. The paper describes the basic techniques of muonic atom spectroscopy and its application. It ends with a description of the muX experiment aiming to perform muonic atom spectroscopy with targets available only in microgram quantities such as the highly radioactive Ra-226 isotope.

Radionuclides for nuclear medicine: the triumphs and challenges by Nick van der Meulen (Paul Scherrer Institute, Zurich).

Terbium is a unique element, as it provides a quadruplet of radio-nuclides suited for diagnostics and therapy in nuclear medicine. Much success has been gained from the PSI-ISOLDE collaboration, with the collection and purification of ^{149}Tb (β-emitter, $T_{1/2}$ = 4.1 h), used for preclinical therapy studies and PET imaging, and ^{152}Tb (β^{+}-emitter, $T_{1/2}$= 17.5 h), for preclinical and clinical PET imaging, respectively. Mass-separated beams of ^{149}Tb and ^{152}Tb, respectively, were implanted at ISOLDE-CERN into Zn-coated Au foils. With 1.5 hours of collection and 2 hours decay of co-implanted activities, up to 200 MBq ^{149}Tb could be transported to PSI. Collections of ^{152}Tb, lasting from 4 to 6 hours, and up to 600 MBq could be shipped to PSI. Both the means of collection at ISOLDE/CERN, as well as the chemical separation system at PSI, have been updated over the years. The Tb was separated from its isobars and contaminants and directly employed for radio-labeling of various pharmaceuticals. PET/CT scans were performed with tumor-bearing mice at different time points after injection of the Tb-labeled radiopharmaceutical in question. The successful experimental runs have prepared the collaboration for proposed extended preclinical imaging and therapy experiments in future. This, along with more regular radio-nuclides produced for nuclear medicine, is discussed in some depth.

From nuclear physics to applications: new detectors for radioactive waste monitoring by Paolo Finocchiaro (INFN-LNS, Catania).

Nuclear physics experiments are always in need of more and more advanced detection systems. During the last years, new technological developments have come out with many improvements in terms of performance and compactness of detector materials, transducers, electronics, computing and data transmission. In light of these achievements, some applications previously prohibitive because of size and cost are now feasible. New radiation sensors are shown and explained, and the radioactive waste online monitoring application is described, starting from the DMNR project at INFN-LNS also being finalized into the MICADO project recently approved by Euratom.

Pedestrian neutrons - tool and object for fundamental physics by Oliver Zimmer (ILL—Grenoble).

Free neutrons moving at pedestrian speed, also called ultra-cold neutrons (UCNs), have low enough energy to become confined and manipulated in traps. Being electrically neutral but being affected by all known fundamental forces they are an excellent probe to study fundamental symmetries and interactions. Storage lifetimes of several hundred seconds enable high-precision experiments with impact on astrophysics and cosmology, complementary to high-energy physics. Although started more than 50 years ago, the search for a non-vanishing electric dipole moment of the neutron is currently a hot topic pursued by many research groups around the world. Increasingly accurate experiments test new scenarios of time reversal invariance violation which is required for an explanation of the matter-antimatter asymmetry in our universe. Also, the neutron lifetime is a key observable investigated with UCNs. It determines the primordial abundances of the light chemical elements after the big bang and is still astonishingly not known with the desired accuracy. A third example of present studies covered in this review is a search for deviations from Newton's gravity law at distances in the micrometer range, using spectroscopy of quantum states of the neutron confined by a horizontal mirror and gravity. Accuracies of most experiments using UCNs are still statistics limited and can thus be much improved with advances in UCN production, which is the goal of an ongoing development of superfluid-helium-based UCN sources at the ILL in Grenoble.

How a small accelerator can be useful for interdisciplinary applications. Part II: cultural heritage studies by Mariaelena Fedi (INFN-LABEC, Firenze).

Archaeometry, i.e., the discipline where science and modern technology are employed to examine archaeological remains, and in general cultural heritage, has now become an important support for archaeologists, restorers and all practitioners in humanities. Among all the possible issues that can raise in the cultural heritage framework, absolute dating and analysis of materials often constitute fundamental questions to be addressed. Nuclear physics, and in particular low-voltage electrostatic accelerators, can allow us to solve such questions. In this review, it is discussed how accelerator mass spectrometry (AMS) through the measurement of radiocarbon concentration and ion beam analysis (IBA) helps us to date organic remains and to study the composition of artworks, respectively. Theoretical fundamentals and some applications are shown.

The extremes of neutron richness by Francisco Miguel Marqus (LPC, Caen).

Is it true that a neutron star can be pictured as a gigantic nucleus overwhelmed by the number of neutrons, unlike real atomic nuclei, that have a similar number of neutrons and protons? What if we could find or create nuclei without protons? How far can we go in neutron richness? Our common sense tells us that these neutral nuclei should not exist, but if they do they would change our knowledge on neutron stars, on the properties of nuclei in general, and ultimately on the nucleon–nucleon interaction itself, the building block of matter. This huge potential impact has pushed some 'crazy' nuclear physicists to search for them since the 1960s. The first positive hints appeared only in the XXI century, and nowadays, several collaborations are trying to corner these weird objects and give a definite answer to this crucial question. In this review, the author goes through this exciting quest, that started with simple experiments and has now reached a stage of ambitious and sophisticated projects, both experimental and theoretical.

Reach for the stars by digging in the dirt by Shawn Bishop (TU, Münich).

Massive stars, which terminate their evolution in a cataclysmic explosion called a type-II supernova, are some of the nuclear engines of galactic nucleosynthesis. Among the elemental species known to be produced in these stars, the radioisotope ^{60}Fe stands out: this radioisotope has no natural, terrestrial production mechanisms; thus, a detection of ^{60}Fe atoms within terrestrial reservoirs is proof for the direct deposition of supernova material within our solar system. The talk reported the direct detection of live ^{60}Fe atoms in biologically produced nanocrystals of magnetite, which we selectively extracted from two Pacific Ocean sediment cores. It is found that the arrival of supernova material on Earth coincides with the lower Pleistocene boundary (2.7 Ma) and it terminates around 1.7 Ma. Additionally, a brief overview of a new r-process actinide search was also discussed.

Hadron therapy: from the conventional approach to laser-driven applications by Giuseppe Cirrone (INFN-LNS, Catania).

Hadron therapy is the most advanced, still pioneering, external radiation therapy approach nowadays available for tumor irradiation. Charged particle acceleration using ultra-intense and ultra-short laser pulses has gathered a strong interest in the scientific community, and it is now one of the most attractive topics in the relativistic laser–plasma interaction research. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields, in particular, medical applications. One of the future biggest challenges consists in using high-intensity laser–target interaction to generate high-energy ions for therapeutic purposes, eventually replacing the old paradigm of acceleration, characterized by huge and complex machines. The peculiarities of laser-driven beams led to develop new strategies and techniques for transport, diagnostics and dosimetry of the accelerated particles, due to the wide energy spread, the angular divergence and the extremely intense pulses. In this framework, INFN-LNS (Italian Institute of Nuclear Physics, Laboratorio del Sud, Catania) in collaboration with ELI-Beamline Institute (Dolny Brezany, CZ) realized and installed in 2018 the ELIMED (ELI-Beamlines MEDical and multidisciplinary applications) beam-line. ELIMED is the first user-addressed transport beam-line dedicated to the medical and multidisciplinary studies with laser-accelerated ion beams and completely open to the scientific community wishing to perform experiments with these new beams. The beam-line permits in-air irradiation of controlled laser-driven ion beams to perform typical multidisciplinary experiments, from biological irradiation to detector tests. The status of Hadron therapy around the world and the potentialities offered by laser-driven beams for its future developments are discussed.

Neutron technique in civil security applications by Sandra Moretto (INFN, Padova).

Non-destructive analysis (NDA) of materials is a well-known technique applied in several fields of bulk material analysis. It is a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage. In particular, focus is on neutron based techniques, like PGNAA (prompt gamma neutron activation analysis), PFNA (pulsed fast neutron analysis), PFTNA (pulsed fast/thermal neutron analysis), API (associated particle imaging), FNGT (fast neutron and gamma transmission). These techniques have big application potential since they could provide data about a large number of elements simultaneously and non-destructively together with valuable imaging and elemental information. For example in industrial applications (oil, coke, concrete) and environmental research (soil moisture, snow). In recent years, significant and rapid developments in technologies such as the neutron sources and detectors together with increasing computer power made it possible to take full advantage of these techniques and significantly broaden the usage of neutron analysis in many different applications. Neutron interrogation techniques generally rely on bombarding the nuclei in the interrogated object with neutrons of particular energy or energies, causing them to emit characteristic γ-rays or alter the energy or the direction of the interrogating neutrons. A general overview of the neutron interactions was presented, together with the main components of these techniques such as neutron sources, detectors and data analysis. Finally, examples were given of application to civil security such as the detection of explosive and more general smuggling in airlines security screening and cargo container inspections.

Nicolas Alamanos, Carlos Bertulani, Angela Bonaccorso, Angela Bracco, David M. Brink[1], Giovanni Casini, Maria Agnese Ciocci, Valeria Rosso and Michele Viviani.

Guest Editors

Acknowledgements The financial support of the following institutions is gratefully acknowledged: INFN, National Theory Group (CSN4); INFN, Commissione Conferenze; University of Pisa and its Department of Physics; INFN, Sezioni of Firenze, Genova, Catania, Napoli, Perugia, Roma1, Bologna, Ferrara, Padova, Milano; INFN, Laboratorio Nazionale di Legnaro and Laboratorio Nazionale del Sud; in particular the IRFU-Saclay for providing also founds for the printed volume. Finally nothing would have been possible without the outstanding professional and human performances of the INFN, Sezione di Pisa administrative and technical staff as well as that of the staff of the Department of Physics and of the Support Summer School, International Cooperation office of the University of Pisa.

[1] Deceased.