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Editorial

Focus Point on Rewriting Nuclear Physics textbooks: Basic nuclear interactions and their link to nuclear processes in the Cosmos and on Earth

This *Focus Point* contains the lectures presented at the Summer School "Re-writing Nuclear Physics textbooks: Basic Nuclear Interactions and Their Link to Nuclear Processes in the Cosmos and on Earth" which was held at the INFN Sezione di Pisa and Department of Physics of the University of Pisa in July 2017. The School followed the format of its first edition (*Re-writing Nuclear Physics Textbooks: 30 Years with Radioactive Ion Beam Physics*) held at the very same places two years earlier, and whose lectures have been published in EPJ Plus[1].

The scope of the event was to attract and educate the best possible students introducing them to the wonders of the Nuclear Interaction as it manifests itself in natural phenomena on Earth and in the astrophysical context. We tried to convey to such students a view of the rich variety of on-going activities in the field, both experimental and theoretical, so that the progress made in the last years can be developed further in the future with the help of the new generation of bright scientists.

The activities were directed towards 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 fifteen lectures. Each lecture covered a topic contained in a standard Nuclear Physics textbook extended to show how our understanding has deeply changed due to the experience accumulated in recent years. In order to give the activity a fully international character, and because we aimed at favouring the participation of really young students, the first half day we proposed some introductory lectures given in separated sessions in different languages. Also, each day ended with tutorial classes in different languages. Lecturers were invited to participate in order to answer the questions by the students. On the last day, we visited the EGO-Virgo laboratory where search for gravitational waves is pursued.

The format of the school was unique and original. There were about 90 participants of which about 60 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 word, now and for several years to come.

In his article, *From the liquid drop model to lattice QCD*, Vittorio Somà describes a brief history of nuclear interactions with the goal of explaining the structure of nuclei. He starts with an overview of gross nuclear properties and how they can be studied with microscopic theories. The path to an *ab initio* calculation is outlined and more effective methods are discussed. These are: a) single-particle models; b) non-interacting shell-model; c) interacting shell-model, density functional theories, etc. Nevertheless, the bulk of the article deals with the latest advances on modern chiral (NN) forces and how recent calculations have accommodated new techniques, such as the similarity renormalization group, allowing to handle the short-range aspect of the NN interaction.

The article *Light and unbound nuclei* by Sofia Quaglioni starts with a general introduction on light bound nuclei, resonances and unbound nuclei as they are studied on Earth. Then it continues showing their importance in Nuclear Astrophysics and, finally, basic models of nuclei are described. Starting from the nucleon-nucleon case, then the few-nucleon problem and finally the many-body problem, various aspects of the structure of bound nuclei are discussed and *ab initio* methods are introduced. Then clustering is explained as a threshold effect in the vicinity of the continuum spectrum. This phenomenon can be taken into account by the resonating group method for two and three clusters. This leads to the no-core shell model with continuum and, finally, introducing R-matrix techniques scattering of nucleons and deuterium can be described. In this way ^{5}He, ^{6}Li, ^{6}He, ^{11}Be are studied as well as the important fusion reactions $^{3}\mathrm{H(d,n)}^{4}$He and $^{3}\mathrm{He(d,p)}^{4}$He.

[1] `https://epjplus.epj.org/component/toc/?task=topic&id=548`.

In his paper *Heavy nuclei: Introduction to density functional theory and variations on the theme*, Gianluca Colò discusses the application of the Density Functional Theory (DFT) to describe the atomic nuclei, their overall features, such as ground-state properties (mass, shape, normal *vs.* superfluid character) and the collective excitations. After an introduction where the main properties of heavy nuclei are summarized, the following sections are devoted to the general description of DFT and to the specific nuclear energy density functional. Finally some examples of application to calculation of masses, radii, nuclear superfluidity and giant resonances are presented. As usual, the author presents the argument in a very clear and exhaustive way, providing the reader with the basic knowledge and arousing the interest for further investigation of the topics covered.

The two articles on nuclear astrophysics (*Introduction to experimental nuclear astrophysics*, by Alba Formicola and Giuseppe Imbriani and *Neutron-induced cross sections* by René Reifarth *et al.*) were very enlightening in explaining how basic inputs from nuclear structure and reactions determine the birth and evolution of stars in the Cosmos. Nuclear astrophysics is indeed a fascinating area of research, which has produced very interesting results and yet requiring new developments to be undertaken in the near and more distant future. The material presented by Alba Formicola, Gianluca Imbriani and René Reifarth makes these points very clear. These papers lead us to appreciating key results and plans towards the solution of interesting open problems in this area of research.

In particular, two topics were addressed, the nucleosynthesis of light elements with its relation to the the reaction rates in a stellar environment, and nucleosynthesis of the elements heavier than iron due to neutron capture.

In connection with the paper on the nucleosynthesis of light nuclei, it is important to highlight the following two points, well discussed after the introductory part on how to determine the reaction rates in a stellar environment. i) The major progress made in the description of burning in stars of light elements, such as hydrogen, helium, and carbon, via precision reaction measurements: Hydrogen burning involves the p-p chain and the CNO cycle for which one of the very important reactions is $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$. This is the slowest CNO reaction and its rate influences the age determination of globular clusters and the solar neutrino spectrum. The results on this reaction are from the LUNA accelerator located at the underground laboratory LNGS. ii) The importance to have new direct measurements of nuclear cross section of astrophysics interest at the Gamow peak: Among the future measurements to be made with the new accelerator LUNA-MV, presently under construction, there are those related to the fusion of $^{12}\mathrm{C}$ on $^{12}\mathrm{C}$. A precise knowledge of the $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ reaction rate is needed since it determines the transition mass between the progenitors of core-collapse and thermonuclear supernovae and, thus, the resulting chemical yields, light curves and spectral evolution. The challenge is the study of $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ fusion reactions using gamma-spectroscopy which can be done only in a deep underground laboratory.

In connection with the paper on the nucleosynthesis of elements heavier than iron via neutron capture reactions, it is important to underline the following issues, which were well illustrated in the articles, after the presentation on how to determine with high precision the experimental cross sections. The activation technique and the time-of-flight method are mostly used to determine the required neutron-induced cross sections in the astrophysically important energy regime between 1 keV and 1 MeV. Even after decades of application, both techniques need improvements and, within this goal, there is the new evaluation of the $^{197}\mathrm{Au}(\mathrm{n},\gamma)$ cross section. New data implied the re-evaluation of 63 other isotopes with experimental information from TOF experiments. To measure the cross section using targets of rare radioactive isotopes, one will need, in the future, more intense neutron fluxes as those of the project SARAF, FRANZ, and NFS at SPIRAL2.

Indirect methods and/or surrogate reactions are often the only possibility to improve our knowledge of the nucleosynthesis of heavy elements involving radioactive nuclei. The Coulomb dissociation method can be used to determine the desired cross sections via the inverse reaction, by applying the detailed balance theorem. Plans to perform relevant studies of the r-process studies are in place and will use the set-up NeuLAND@FAIR. The planned measurements will exploit the availability of radioactive nuclei, at FAIR, at the vicinity of the neutron drip line and the excellent energy resolution of the neutron detection system at the R3B set-up.

The subject of the paper *A short walk through the physics of neutron stars* by Isaac Vidanaa is a rich survey of the very special systems that neutron stars are. The author introduces the reader to the historical development of the ideas concerning these strange objects where nuclear matter is found at extreme conditions. From the first hypotheses on the existence of dense nuclear systems surviving at the end of the life of ordinary stars, neutron stars have demonstrated to be a rich laboratory of ideas and phenomena, whose description needs the contribution of interdisciplinary theoretical concepts and experimental techniques. These range from nuclear science to radioastronomy, from hydrodinamical models to gamma ray spectroscopy and to gravitational wave detection.

Neutron star science developed in the 20th century. With the progress from the first ideas in the 1930s to the discovery of strange pulsed radiosources (pulsars) in the 1960s, up to the very recent opening of the multimessenger era in 2017, the physics of neutron stars has become, year after year, one of the most challenging branches of modern research. Now these systems, quite small on the astronomical scale but enormous on the nuclear one, are supposed to possess a complex internal structure with different layers, from the core to the surface. While in the core the existence of hyperons is strongly supported by data and deconfined quarks are postulated, the region close to the surface represents a special and unique phase for asymmetric nuclear matter. The paper guides the reader on this path, showing how the different physics concepts contribute to describing the properties of neutron stars.

Alessia di Pietro describes, in her article *Phenomenological optical potentials*, how the elastic and the inelastic nuclear scattering and a plethora of processes in nuclear scattering deeply depend on the details of nuclear optical potentials. She draws a review of basic scattering theory, and discusses scattering phenomena, such as orbiting arising from the interplay of nuclear and Coulomb interaction. Among many applications, she discusses in detail the threshold anomaly in fusion reactions and dynamic polarization potentials. Other applications of recently developed folding potentials are also discussed to explain nuclear scattering data.

In *Direct reactions as quantum probes for nuclei* by Susumu Shimoura, the essential theoretical tools for obtaining information on the properties of exotic nuclei are presented. The development, worldwide, of new rare isotope beam facilities and their associated experimental equipment has considerably enhanced the number of exotic nuclei that can be reached and studied using these tools. The author did not forget the experimental physicists when writing the article, and to comply with the well-known request of the past Chairman of the Division of Nuclear Physics of the American Physical Society, Evans Hayward, for theoretical lectures to have “words between the equations”. This paper is of great interest to those engaged in active research in nuclear reactions and it is also meant as a guide and an introduction to this vast field for graduate students in general.

The paper *Symmetries and fundamental interactions: Theory* by Luca Girlanda discusses symmetries and fundamental interactions, in particular gauge principles.

Spontaneous symmetry breaking is a situation in which the symmetry of the Lagrangian is not the symmetry of the world. An example is the theory of superconductivity, in which a charged scalar field, representing electron Cooper pairs, acquires a vacuum expectation value, as a result of the shape of the potential function acting on the Cooper pairs. In the same way, the spontaneous symmetry breaking of the $SU(2) \times U(1)$ gauge group is at the basis of the unified electro-weak interactions to the massive gauge bosons W and Z, which are mediators of weak interactions.

The idea of chiral symmetries implies that there are left-handed and right-handed particles and the Lagrangian is symmetric with left-handed and right-handed quarks. Chiral symmetries are clearly broken because there are no left-handed and right-handed pairs of elementary particles.

The last section of the paper derives an effective interaction for a collection of nucleons, based on the Gell-Mann-Oakes-Renner (GOR) relation, which involves both explicit chiral symmetry breaking and the spontaneous breaking of the quark condensate. The GOR has an order parameter analogous to the spontaneous magnetization for spin systems. The effective interaction is the sum of 2- and 3-body terms and the parameters are fitted to nucleon-nucleon observables. The effective good interaction is used to calculate energies of light nuclei up to ^{11}B. There is good agreement with experimental data.

In *Symmetries and fundamental interactions: Precision experiments at low energies* by K. Kirsh, it is shown that precision physics experiments at low energies, employing nuclear physics methods in particular, may be used as a probe to address some of the most fundamental questions of physics. These questions are: Do we really understand the known interactions? Are there more, as yet unknown, forces? Which symmetries of nature remain unbroken? What are the precise values of the fundamental constants? Are the so-called fundamental constants actually constant? (And so on.) The author has chosen an illustrative approach, giving examples of such experiments, addressing various aspects of the known fundamental interactions and the associated open issues. The aim of the paper is to attract the readers' interest and provide starting points for further studies.

The paper *Resonances in neutron-induced reactions* by Frank Gunsing is concerned with neutron-induced reactions which play a major role in nuclear technology for energy and medicine. A characteristic of neutron reaction cross sections at low energies in heavy nuclei is the presence of resonances. A nucleus has a fairly sharp surface. When a scattered nucleon is outside the target nucleus, the wave function can be written as the product of the target nucleus wave function and the wave function of the scattered neutron. In the internal region, when the scattered nucleon is inside the target, the neutron is absorbed and the wave function becomes very complicated and one speaks about a compound nucleus state.

In the R-matrix theory, one considers an internal region of radius R where all the nucleons are inside the sphere and solves the Schrödinger equation for all the nucleons with appropriate boundary conditions on the sphere. Then, one matches the internal wave function onto an external scattering wave function with one nucleon outside.

For thermal neutron scattering by either a medium or a heavy nucleus, the scattering is dominated by s-wave resonances. Near a resonance, one has either elastic scattering or neutron capture, followed by emission of gamma rays. The cross section can be described by the Breit-Wigner single level approximation, which depends on parameters. Gamma ray capture cross sections fluctuate from one nucleus to another and are expected to follow a Porter-Thomas statistical distribution. This distribution has been studied and verified for many data sets.

Vincenzo Patera and Ilaria Matteri, in *Nuclear interactions and medicine*, introduced the very important subject of hadron interaction in matter, with particular focus on the applications of such interaction to medicine and human health. Indeed, energetic hadron beams can be used as a tool to treat localized and deep tumors more effectively than exploiting conventional photons or electrons. Apart from this relatively new and still developping field in nuclear medicine, there is another context, where the detailed study of the hadron interaction in matter is very important. This is the space exploration via interplanetary human missions; in these long journeys, humans are exposed to fluxes of extremely energetic hadrons from intergalactic sources. The evaluation of the dose in this case is relevant to the construction of the best shielding devices. The lecture introduced well to the students the background of this field, first explaining the benefits and the limits of both conventional and new methods in radiotheraphy. From this introduction, the need for further experimental studies in the field of precise dose evaluation appeared quite clear; these are aimed at maximising tumour destruction while saving healthy cells. In this respect, modern experimental studies are focused on the evaluation of the side effects that are unavoidable with hadron beam therapy. In the case of irradiations with heavy α or carbon beams, the original ions undergo fragmentation and the various clusters emitted along the path in the body can be the source of spurious dose deposit in the surrounding healthy tissue. Also, fragments can be produced from the target nuclei, *i.e.* the ones composing biological soft tissues and bones, like carbon, oxygen and calcium. The paper presents the above-mentioned aspects, within the general frame of modern hadrontherapy applications, without neglecting the strict connection between precise experimental results on fragmentation phenomena and the refinement of treatment plan codes, which are the essential basis for the individual cycle of irradiation for every patient.

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Guest Editors