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Physique Nucléaire et Astrophysique Nucléaire

Addressed aspects

- 1. Emerging new directions in the low-energy nuclear-physics context and their links to interdisciplinary concepts
- 2. Bridges and synergies between different theoretical domains that could be beneficial for the community, also to strengthen the theoretical support for experimental activities. (For instance, bridges between ab-initio models and energy-density functionals)
- 3. Towards consistent theoretical description of nuclear structure and reactions

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Context

Nuclear physics has strongly progressed during the last years with significant achievements in the understanding of the nuclear interaction and in the development of sophisticated many-body and few-body models. Recently, with important advances in effective-field theories (EFTs), especially in the low-energy QCD nonperturbative sector, new interactions have been designed that are appropriate for solving the nuclear many-body problem. This has opened new opportunities in particular to link QCD to low-energy nuclear physics and to perform so-called exact ab-initio calculations that flourished worldwide. The applicability of ab-initio methods is however restricted in a relatively narrow region (mostly small masses and closed-shell nuclei, even if important extensions were done in the past years) and many areas of nuclear physics cannot yet take advantage of these achievements.
On the other hand, the nuclear energy-density functional (EDF) theory is a powerful and versatile approach for the nuclear many-body problem. It allows for a unified description of static and thermodynamic properties of nuclei all along the nuclear chart, up to the heaviest elements existing in nature. EDF may also be applied to very extended systems like neutron stars giving insight in selected astrophysical observations. Its time-dependent version provides a microscopic description of a variety of dynamical phenomena, ranging from collective surface vibrations, and binary reactions, to the fission process. It is however clear that the empirical ingredients used to build nuclear EDF reduce its predictive power in the yet scarcely explored physics of exotic nuclei.

Addressed aspects

1) Emerging new directions in the low-energy nuclear-physics context and their links to interdisciplinary concepts

Starting from their birth in the 70s, with the first mean–field (MF) calculations carried out for the ground state of spherical nuclei, nuclear EDF theories have evolved over time following two main directions: on the one hand, a **continuous and intense effort** was devoted to generalize and implement the employed **effective density functionals**. On the other hand, the **necessity to formulate** and develop more **sophisticated beyond–mean–field (BMF) models** has become over the years a clear evidence.
Nowadays, several **EDF BMF models** are available for structure and reaction applications. Mutual exchanges between practitioners working on each of these two directions (functionals and models) have been extremely beneficial and have led to significant progress and achievements in both sectors. These mutual exchanges have also opened the doors to a new challenging direction that is the generalization of EDF functionals and the introduction of a **new generation of functionals designed for BMF applications**. Related to this, the construction of ab–initio–based or ab–initio–inspired EDF functionals became an important goal (see point 2)).

The nuclear EDF frame was formulated, in the first years of its life, in tight connection with MF calculations carried out with effective interactions. The parameters of these interactions were adjusted (with the same MF calculations) and this provided a coherent and closed framework where such applications were done. In a certain sense, since the parameters were adjusted to reproduce selected observables, the associated functionals contained correlations that were absent in the employed many–body model and could indeed provide a quite accurate description of several properties of nuclei. This somehow resembles the concept of a universal functional which is the basis of the density-functional theory (DFT) and which, within the DFT, is expected to provide in principle the exact description of a many–body system.

In the past years, special attention was devoted to clarify and rigorously identify the **links** and the **differences existing between nuclear EDF theories and the DFT developed for electronic many–body systems and employed since decades in quantum chemistry and solid–state physics (interdisciplinary aspects)**.
It is important to open a parenthesis here and to stress that a very promising direction which is important to pursue in the next years is indeed related to the **interdisciplinary links which exist with the large many-body community** (chemistry, solid state physics, atomic physics). Initiatives have been proposed along this direction recently (for example, the creation of the GDR NBODY was the initiative of theoreticians in chemistry - the first meeting of this GDR will take place in January 2020 in Lille and will involve also nuclear theorists). This can be beneficial for nuclear many-body theorists who can learn new techniques and approaches and who can on the other side 'export' their skills and their modern developments. Nuclear physics can thus merge with other domains and the way the other domains view nuclear physics may be strongly impacted.
Also, these interdisciplinary bridges can be extremely important in the prospective of having **a many-body community unified in the common interest of being involved in future possible quantum computation** (see other contribution centered on QC). Related to this, for the IN2P3 community, a first exploratory meeting on quantum computing was organized in Orsay by ourselves (this is discussed in the other contribution).

If one strictly remains in a genuine DFT–like spirit, it is quite puzzling to try to include in the same EDF concept the theories which were formulated in the past decades to overcome the MF approximation.
In the nuclear case, the EDF framework was developed in a quite empirical and pragmatic way and not based on a founding theorem as DFT. Also, MF–based models were not rigorously formulated within a defined guiding approximation scheme (such as a low–density expansion or the Dyson many–body perturbative expansion) that could allow for a systematic improvement of the theory order by order.
This being said, we know that during the last decades numerous BMF models have been formulated and that, in most cases, they were based in practice on the same density functionals used for MF applications. On the other side, one may notice that the MF approximation indeed corresponds to the leading order of the Dyson many–body perturbative expansion. In this sense, BMF models may be seen as approximations where higher orders of such an expansion are included (with all the precautions that one has to take in order to handle double–counting problems and possible divergences).
In this perspective, one may conceive to **extend the EDF concept and** to **include in it BMF models based on effective interactions and/or higher orders of the perturbative Dyson expansion**.

Also, it is important to pursue the efforts in **implementing and rendering more refined BMF models. Nowadays, important implementations of the associated theories may indeed be more easily included in the numerical applications thanks to the strongly improved computational power (HPC for example).** Complex correlations may be more easily described. In this context, on a more long-range perspective, one may also foresee future implementations related to quantum computation for many-body systems.

To resume, point 1) covers the following questions of the NuPECC long-range plan.

- ***Comment les propriétés générales des noyaux atomiques émergent des interactions fondamentales sous-jacentes ?*** (work on the functionals/interactions tailored for BMF models and interdisciplinary links with DFT)
- ***Comment la structure nucléaire évolue le long de la carte des noyaux ? : propriétés fondamentales, limites de stabilités, structure en couche et déformation, chemin vers la complexité.*** (work on refined beyond-mean field models containing correlations: better description of nuclear structure)
- ***Comment les systèmes nucléaires et les corrélations entre leurs constituants élémentaires changent sous conditions extrêmes de densité, température, moment angulaire et isospin ?*** (complex correlations included in beyond-mean-field models)

2) Bridges and synergies between different theoretical domains that could be beneficial for the community, also to strengthen the theoretical support for experimental activities. (For instance, bridges between ab-initio models and energy-density functionals)

Together with the design of functionals adapted for BMF models, the construction of bridges between EDF and ab–initio models and EFTs is a challenging objective which is extremely important to be attained in the present context of nuclear theory. It turns out that sophisticated BMF models are available and represent powerful formal and numerical tools for addressing complex correlations and complicated phenomena in structure and reaction theories. It is worth mentioning that EDF-BMF methods have been constructed following the principle that the algorithm should scale polynomially with the number of constituents of the problem under consideration. This particular advantage makes EDFs to constitute nowadays a unique and the most versatile way for describing nuclei in both structure and reaction studies, practically covering the whole nuclear chart. On the other hand, ab initio computations often scale as the square of the problem size (or, worst, combinatorially), with little hope of improvement of the algorithms or many-body-expansion methods, but offer few cases where the bare nuclear interaction can be understood and EDF method benchmarked.
However, current EDFs can be coherently utilized only for MF applications, owing to the procedures utilized to build them. The adjustment of the parameters carried out at the MF level and the occurrence of instabilities and divergences make questionable their use in BMF models. Generalizations of them or ad–hoc procedures (such as subtractions) are necessary for a proper use in a BMF framework. Also, current EDFs are essentially phenomenological and this may have a strong impact for example on their predictive power in the regions of the nuclear chart which are still far from observation. In the last decades, important efforts have been put in USA to make nuclear EDF less empirical particularly following density matrix expansion scheme. However, it seems that little success has followed from this path. Therefore, it is more promising to capitalize on the fine-tune ingredients encoded in ab initio interaction (e.g. tensor, spin-orbit, three-nucleon force etc…) and the possibility to benchmark EDF on simple systems where the many-body problem can be solved with a good approximation.
At the same time, the last years have seen a tremendous progress and remarkable achievements in the development and in the applications of ab–initio models to nuclei, not only to the lightest ones and not only to closed–shell nuclei. **Merging competences and expertise coming from both EDF and ab–initio practitioners may definitely bring in a close future to important advances in the construction of a coherent, versatile, and fully microscopic description of nuclei for structure and reaction studies, as well as, in nuclear astrophysics, for the description of nuclear systems located in the crust of neutron stars.**
In recent years, attempts have been made to bridge modern aspects of nuclear physics and nuclear EDF with the goal to render less empirical the latter approach and to directly link the EDF ingredients with properties of the underlying quarks and hadrons. Such bridge is particularly challenging and would promote the nuclear EDF also as an ab-initio method. In parallel, this would also remove part of the uncertainties in the construction of a nuclear EDF and offer a practical unambiguous and ambitious tool to describe nuclear systems.
The directions to be followed in this sense are:

1) Validating a strategy for **designing ab-initio-type EDF functionals**, based on completely microscopic ingredients and benchmarked on ab-initio EFT-based results (work done also on the equation of state of matter at different density regimes).
2) Progressing on the **definition of a power counting for EDF** to unambiguously associate functionals to each order of the perturbative many-body Dyson expansion (for instance for mean-field and beyond mean-field models).
3) Using **microscopic functionals to generate systematic predictions for applications to study low-lying modes, giant resonances, spectroscopy, …**
4) **Using also properties of Fermi gases at the unitary limit** (universal behavior) to further reduce (or eliminate) the parameters dependence of our new-generation EDF functionals.
5) Use many-body methods, adapted to both EDF and bare interactions, that can genuinely construct a Kohn-Sham like potential embedded in the many-body space to parametrize the EDF, particularly components of the effective force typically related to long-range interaction.

To resume, point 2) covers the following questions of the NuPECC long-range plan.

- ***Comment les propriétés générales des noyaux atomiques émergent des interactions fondamentales sous-jacentes ?*** (work on ab-initio- or EFT-inspired functionals/interactions)
- ***Comment la structure nucléaire évolue le long de la carte des noyaux ? : propriétés fondamentales, limites de stabilités, structure en couche et déformation, chemin vers la complexité.*** (work on beyond-mean field models and on the improvement of the predictive power of functionals (less phenomenological ingredients))
- ***Comment les systèmes nucléaires et les corrélations entre leurs constituants élémentaires changent sous conditions extrêmes de densité, température, moment angulaire et isospin ?*** (correlations included in beyond-mean-field models using more microscopic (ab-initio inspired) functionals)
- ***Quelles sont les propriétés de la matière dans des conditions extrêmes de densité et de température qui permettent la compréhension des étoiles compactes et de leur évolution ?*** (work done also on the equation of state of matter at different density regimes).

3) Towards merging theoretical nuclear structure and reactions

To date a faithful microscopic description of nuclei and nuclear reactions (i.e., whose theoretical uncertainties are equivalent to those of measurement) remains an unfinished challenge. Any fundamental research involving nuclear reaction must rely on simple yet well-suited models, which however lack predictive capabilities, or data rather than an established theory of the atomic nucleus. In a recent report made on challenges for nuclear reactions made on the occasion of the GANIL community meeting in 2019, 25 topical items were identified, 7 of which remain almost untouched. Among them, some reaction mechanisms are so uncertain that they restrict our understanding of fascinating phenomena such as nuclear halo, extremely loosely bound systems that show universal aspects of a few-body systems such as scaling laws– i.e. they do not encode details of the strong force. However, reaching a complete understanding of these nuclei requires both a precise description of nuclear correlations and an accurate accounting of large-distance behaviour, currently out of reach.

Among the listed challenges, some are ingredients of **the standard probes used to study exotic nuclear systems**. Others **hindered our understanding of nuclear dynamic** (e.g. fission) or **engineering capabilities to design new radioactive beams** from the collisions of heavy ions. All reaction probes are essential to our understanding of nuclear shells, nuclear halos in light exotic systems, and clustering in nuclei. We list below only two directions because they constitute the simplest cases for which experiments can be made such that complexity of reaction mechanism is **minimal** (e.g. no final state interaction, no thermalization, no fission, no tunnelling, no low-energy transfer, no fragmentation etc… needless to say that it is a long way to go):

a) To achieve the modelling of high-energy breakup reactions starting from inputs that fully describe the structure of bound states at the vicinity of the particle emission threshold. This coincides with the challenge that consists of making a consistent transition from low-energy physics to high-energy dynamics.

b) To establish a method to compute predictive optical potentials of equivalent or better fidelity than the currently used phenomenological potentials in reaction theory. Together with the goal of expanding the mass reach of *ab initio* or EDF reaction formalism, this will work towards the goal of moving from reactions involving few constituents to many-body reacting systems.

So far, little efforts were devoted to bridge the gap between low-energy structure, particularly for shallow states like exotic cluster or halos, and practical experimental observables. Indeed, many experimental facilities investigate exotic systems in inverse kinematics at **higher relative energies** than the prototypal low-energy expansion used in many-body methods. It was established that breakup and knockout reactions are mostly peripheral, e.g. requiring the asymptotic normalization coefficients (ANC) to be correctly reproduced by the microscopic structure method. While this represents a daunting task for standard methods which rely in harmony oscillator expansion or cubic box of a few Fermi in size, this is doable and should now be used in standard high-energy reaction breakup models. On the other hand, only a few propositions have emerged for optical potentials derived from microscopic theory. They all suffer from a poor description of the nuclear absorption. There is much work to do in that direction but any progress will strongly increase the predictive power of direct nuclear reaction model.

Besides the consistent description of reaction mechanisms used to probe nuclear structure problem, the description of small and large amplitude collective motion in nuclei presents an enormous richness of microscopic phenomena. In most cases, such phenomena are rather well understood using rather simple intuitive models and can eventually be described using the more microscopic time-dependent version of the nuclear EDF discussed in item 1). Despites the important progresses made recently in particular due to the inclusion of superfluid effects in the time-dependent EDF (TD-EDF). In most nuclear phenomena only the gross features are understood and a large number of interdisciplinary questions remains largely open. We select some of them that deserves attention in the future:
a) Mean-field approach, while treating single-particle states as quantum objects provides a classical for collective observables. There are numerous signatures of the quantum nature of collective degrees of freedom pleading in favor of a proper re-quantization of mean-field. A practical solution to this problem is missing. This problem is a general difficult that is directly connected to more practical difficulties like (i) how to describe competing channels in a mean-field based picture? (ii) how to describe (deep) quantum tunneling in interacting Fermi systems? (iii) What is the connection between configuration mixing and spontaneous symmetry breaking in mesoscopic systems? …
b) As discussed previously in items 1) and 2), a challenge for the next decade is the development of a consistent EDF-BMF framework that is inspired and take advantage of most recent ab-initio and effective field theory progress in nuclear physics. Any progress made in this direction can be beneficial also for the equivalent time-dependent version of the novel EDF. Therefore, consistently with the effort that should be made to provide less-empirical EDF, one should in parallel develop a consist new generation of TD-EDF that has increased connections with ab-initio methods while being able to address interesting problems over the whole nuclear chart.

With the advent of radioactive ion beam facilities, like our national GANIL/SPIRAL2 program and the FAIR facility in Germany, the understanding of exotic systems is nowadays the next frontier for nuclear physics. Unfortunately, it is often the case that no model independent connections can be made between the nuclear structure calculation and the experimental observables, e.g. theory may compute low-energy structure properties while experimentalists probe high-energy scattering and breakup reactions. Another important step, in particular to be able to produce yet unknown nuclei, is to provide strong guidance on the reaction mechanisms that are anticipated to form them. This implies for instance a perfect microscopic understanding of the transfer, fusion and/or fission processes as well as their competitions. Any progress in the direction of providing **a direct link from nuclear structure calculations to experimental** measurements will **strongly benefit our understanding** of the nuclear interaction and its application.

To resume, point 3) covers the following questions of the NuPECC long-range plan.

- ***Comment arriver à une approche unifiée pour la structure et les réactions ?***