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Linear-response Theory and the Nuclear Force

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ABSTRACT

With new and upgraded rare-isotope facilities in Asia and across the world and newly available "multi-messenger" astronomical observations, nuclear physics is preparing for discovery with a wealth of tools at hand. Among those tools, the random-phase approximation (RPA) has been widely used as a linear-response theory and at the same time as a framework for learning from observable nuclear collective motion about the exotic regimes of the nuclear equation of state (EoS) – as realized in neutron-rich nuclei and compact stars. Currently, a bridging is being undertaken, not only of collective motion with the EoS, but also of both of them with more fundamental entities like the nuclear Hamiltonian. A learning feedback cycle ensues, by testing new Hamiltonians on collective phenomena and taking those lessons over to the development of convenient but realistic energy-density functionals. A small segment of progress in the field is reviewed here, using nuclear giant resonances as case studies.

INTRODUCTION

At length scales of a few femto-meters, namely the size of an atomic nucleus, and frequencies reaching roughly a hundred zetta-Herz, we find the sound-wave analogues and normal modes of oscillation of a quantum nuclear liquid drop; surface and density vibrations, spin-isospin oscillations, and a variety of so-called *giant* and *pygmy resonances* [1, 2], are driven by a variety of restoring forces. Giant resonances are defined as structures in the nuclear spectrum in a specific isospin T, spin S, and angular-momentum (multipole) channel L, which exhaust a high percentage (more than half) of a corresponding energy-weighted sum rule in that channel. Typical and easy to visualize examples are: a) the isoscalar giant monopole resonance (GMR), or the breathing mode, corresponding to the overall compression of an atomic nucleus (T=0, S=0, L=0); the restoring force is related to the compression modulus of baryonic matter; and b) the isovector giant dipole resonance (GDR), corresponding, in a simplified picture, to a displacement between the proton and neutron "fluids" in the nucleus (T=1, S=0, L=1); the restoring force is related to the nuclear symmetry energy. Weaker resonances in terms of sum rules, but still classifiable as collective resonances, such as various surface modes, are also driven by restoring forces with some connection to the nuclear equation of state, especially in dilute regimes found on the nuclear surface. All these types of collective excitation are of fundamental interest for determining the nuclear equation of state and as manifestations of the underlying nuclear forces [3].

Many different projectiles and detecting devices have been utilized over the past decades to excite and identify those fundamental modes and to study their decay. The primary goals are to extract information on isospin-asymmetric and other exotic forms of baryonic matter, produced in heavy-ion collisions and realized in compact stars, and to accurately model nucleosynthesis paths, while making the most of new rare-isotope facilities such as RAON [4] and of newly available astronomical observations in the so-called multi-messenger astrophysics era [5].

Determining the connection between a finite droplet and an infinite system is generally a theoretical challenge.

The most natural framework to achieve the formal connection is arguably energy density functional theory, while a more fundamental one, in some sense, must involve explicitly nuclear forces inducing a variety of correlations.

First, I will briefly review some of the complexities that specifically compound the theoretical description of nuclear systems and then I will focus on extensions of the random-phase approximation, which represent linear-response theory and therefore a link between the EoS (as represented by the restoring forces of vibrational excitations) and the underlying interactions among nucleons.

I note that in the following, the energy per particle or the energy density of infinite nuclear matter will occasionally be invoked to represent the nuclear EoS. The discussion will be restricted to zero-temperature nuclear systems and to non-relativistic (non-covariant) theoretical frameworks. We will not consider clustering.

NUCLEAR MANY-BODY PROBLEM(S)

Let us briefly review the basic features of the nuclear many-body problem and the problems it presents.

A nuclear system can be defined very simply as follows: There are A nucleons (Z protons and N neutrons) in relative proximity. The number A spans $10^{0\sim2}$ for isolated atomic nuclei, but generally can be arbitrarily large. The nucleons subject each other to (at least) two- and three-nucleon potentials of strong-nuclear origin – NN(N) for short; the nuclear Hamiltonian includes the NN(N) potentials, potentials of electroweak origin, and the nucleons' non-relativistic kinetic energy. The chosen nuclear degrees of freedom here are not the fundamental ones of quantum chromodynamics (QCD), namely the constituent quarks and gluons, but supposedly inert nucleons in the non-perturbative regime of QCD.

It is possible to proceed to study the nuclear phenomenology and EoS without defining a Hamiltonian at all, but only the energy density, in the framework of energy density functional theory (DFT). This has been a very fruitful program for decades [6, 7]. At the same time, to rely solely on a realistic nuclear Hamiltonian (one that describes realistically the static and dynamic properties of few-nucleon systems) for the system's quantitative description is the goal of *ab initio* programs of nuclear structure, see, e.g., [8-11]. If we were to solve the corresponding Schroedinger equation for the A-nucleon wave function, we would need to obtain all information possible for the system of nucleons at energies below the nucleon excitation energy. There is a fertile exchange between the DFT and *ab initio* programs, as recent activity demonstrates [12, 13].

The complications of the Hamiltonian approach arise at both the conceptual and the practical level. The conceptual issue has to do with the definition of the nuclear Hamiltonian. Far from being point-like, inert particles, the nucleons have a finite size comparable to typical distances in an atomic nucleus and a high but finite excitation energy comparable with scales commonly reached in heavy-ion collisions. The presence of a three-nucleon force already implies that the nucleons are polarizable (not inert). Clearly, the Hamiltonian must be an *effective* one on some level. This holds for both meson-exchange potentials and those developed from chiral effective field theory [10, 11]. Reducing the nuclear many-body problem to the formally simpler level of Landau-Migdal theory, one may define *quasi-particles* [14]. Major effects of the intra-particle interactions are absorbed into the properties of dressed versions of the particles. Those now interact via *in-medium* potentials – or do not seem to interact except through a common mean field and residual interactions, *cf.* the Hartree-Fock approximation (HF). One concludes from the above that the NN(N) potentials are not uniquely defined.

The practical issue is that the many-body Schroedinger equation is not solvable as such. As with any interacting many-body system, exact (or practically exact) solutions are only possible for small numbers of nucleons or in the thermodynamic limit of infinite matter. Enormous progress has been made in this direction through the use of quantum Monte Carlo and no-core shell-model approaches, which have provided calculations for the ground state energies, charge distributions and form factors, and low-lying spectra of light nuclei [8-10, 15, 16]. However, and especially for heavy nuclei and higher excitation energies, the full equation must be replaced with a suitable *quantum many-body method*, which introduces some informed hierarchy to the nucleon configurations considered, which in turn may depend on (be tailored for) the problem at hand. The choice often reflects the emergent character of the studied phenomena, which we only recognize *ad hoc*, and the inherent impossibility of predicting their existence before any observation. A straightforward example is the linearized time-dependent HF approximation, equivalent to the first-order *random-phase approximation* (RPA), [1, 2, 3, 17] which is suitable for the description of collective, small-amplitude vibrational states. An example of a systematically improvable many-body method is the coupled cluster method, corresponding to an accountancy of configurations up to a certain order of m-particles-m-holes (*mp-mh*) [18]. Among recent successes of the latter, used in combination with the Lorentz integral transform method, we may mention a calculation of the photoabsorption cross sections and polarizabilities of Ca isotopes [19].

Compounding the above concerns is the singular behavior of the NN(N) interaction at short distances, which induces strong *short-range correlations* (SRC) in the many-nucleon system [17, 20-22]. The latter do not allow for a perturbative treatment. Within a rich ongoing line of theoretical research, the high-momentum components of the so-called "bare" interaction can be "integrated out" or "renormalized" or "softened" or "pre-diagonalized", etc., so as to eliminate any explicit contribution and thus facilitate convergence and almost exact solutions [23]. At the same time, families of NN(N) interactions are developed within chiral effective field theory [11, 24]. It follows again that the NN interaction is not unique (in the sense that, e.g., the Coulomb potential is unique) because it is far from fundamental; families of phase-shift equivalent NN interactions have been defined over the years with various methods. Given that SRCs are quite selective in their explicit manifestation, for many phenomena of interest the above approaches are perfectly legitimate. In another line of research, the correlations are treated with diagrammatic methods [25, 26]. Collective nuclear response in fermion systems has been explored in the past with correlated versions of RPA, which combine linear response theory with correlated basis states [27].

The above "complications" are not nuclear-specific, of course. Quasi-particles, effective interactions, in-medium effects, correlations, phonons and collectivity, are encountered in a variety of quantum many-body systems, encompassing quantum solids, liquids, and gases, bosonic and fermionic, in three or fewer spatial dimensions. One generation's elementary particles are the next generation's many-body systems. An additional complication of the nuclear many-body problem is the size of a typical nucleus: finite nuclei are very small systems. Unlike the situation in, e.g., nano-droplets with thousands of atoms, the number of nucleons in the nuclear bulk is comparable to that on the diffuse nuclear surface, if not smaller. The bulk population of heavy nuclei is still far from the thermodynamic limit, thus a typical nucleus must always be studied as a finite system. One implication is that various surface and volume phonons often couple, producing a complex excitation spectrum [28]. A nucleon interacts and exchanges energy not only with individual nucleons, but also with the nuclear surface through surface phonons. The coupling to surface phonons induces *long-range correlations* (LRC), which influence surface and threshold phenomena. In general, phonons in the bulk of a quantum many-body system represent LRC that influence the system's dynamics. They are responsible, for example, for screening effects in electronic systems and the development of superfluidity in quantum liquids. In the bulk of large enough systems, the effects are decoupled from surface phonons and can be studied separately. In the case of finite nuclei, however, the energy and length scales of surface and volume phonons are comparable [29].

In addition to the issue stated above, we may add that the center-of mass-motion of the small, finite system that is the atomic nucleus needs to be projected out of the intrinsic nuclear states in theoretical approaches [30].

To summarize, the description of finite nuclei is complicated by the interplay of SRC and LRC of surface or volume type. Although phenomenological approaches exist to describe a variety of individual effects, a consistent many-body theory of the combined effect of SRC and LRC remains an immense but also exciting challenge.

Scope of the present exposition

In the section above, we summarized the nuclear many-body problem in very broad strokes. Let us now fill in some details and define the scope of the present work.

As already stated, we are interested in collective excitations known as giant and pygmy resonances, in the excitation-energy regime of a few MeV to roughly 20 MeV [1-3] - corresponding to roughly 10^{23}Hz in frequency units. Many nucleons contribute coherently to collective modes.

Our overarching interest lies in the bulk properties of nuclei, i.e., nuclear-matter properties such as the compression modulus and symmetry energy mentioned above as drivers of collective vibrations. We are also interested in energy dissipation mechanisms that originate in nuclear interactions and drive the internal damping of such resonances. Therefore, although some of the phenomena under study require the presence of a nuclear surface, we also learn from them about homogeneous matter at different densities.

Best suited for disentangling the bulk from the surface phenomena are, in the author's view, magic nuclei. First, magic nuclei are stiffer with respect to surface vibrations and thus in principle offer a cleaner "bulk signal". Second, they are always spherical, which greatly simplifies their theoretical description, i.e., theoretical uncertainties are reduced. Third, closed valence shells eliminate the need to consider residual pairing interactions among valence nucleons, which would add to theoretical uncertainties.

TWO VIEWS OF THE RANDOM PHASE APPROXIMATION

At present we consider the random-phase approximation (RPA) and its extensions. The basic RPA that we consider is particle-hole (*ph*) RPA (ring diagrams), with particle and hole states defined in reference to a Hartree-Fock (HF) particle-hole vacuum. We will denote that as HF-RPA. Among the formal properties of the RPA solutions we note that, in the absence of instabilities, a) physical solutions of positive norm appear at real, positive energies and their adjoint solutions of negative norm appear at the opposite (negative) energies; b) the energy-weighted sum rule is preserved with respect to the HF expectation value and therefore c) spurious solutions corresponding to broken symmetries of the HF state (typically translational and rotational invariance) are automatically obtained at zero energy, i.e., restored outside the physical spectrum. The appealing properties of HF-RPA as a self-consistent, symmetry-restoring formalism have been well documented [17, 31].

Long-range correlations in the ground state can be quantified with the help of HF-RPA [31, 32]. In fact, this type of RPA occupies a high rung in the "Jacobs ladder" of electronic DFT [33]. Its status in nuclear physics is complicated by the importance of SRC and the need to consider various types of diagrams.

Extensions of RPA may include, for example, *mp-mh* configurations in the ground state or the excited state or both. The term *Second RPA*, in particular, will refer to the inclusion of $2p$-$2h$ configurations in the excited states, but still in reference to a mean-field or perturbative ground state [34, 35]. If the reference state is the HF state, we may call it self-consistent HF-SRPA. The term "self-consistent" is used here to refer to an implementation where the only input is a nuclear Hamiltonian – as opposed, for instance, to an empirical mean field and an unrelated residual interaction (i.e., the term as used here does not imply that the theoretical framework itself is self-consistent in some deep sense). The formal properties of self-consistent HF-SRPA are largely the same as those of HF-RPA [36] with the important difference that the HF reference state is no longer expected to guarantee a stability condition [37]. It is now possible to have solutions at real, positive (negative) energies with a negative (positive) norm. As a result, even though the EWSR is conserved, spurious states may appear at finite energies. For more details, see [37]. Clearly SRPA is not appropriate for applications indiscriminately. However, it remains acceptable for highly collective states that are only weakly affected by explicit ground-state correlations [38, 39].

Generally, extensions of RPA may involve a correlated ground state (beyond HF, or beyond "mean field"), coupling of *ph* to *mp-mh* configurations, coupling of particle and hole states to collective phonons, and so on. There is much ongoing and promising progress [40-44]. The classification may follow analogous classifications of Green functions. The full literature spans disciplines and is too vast to adequately describe, so let us instead focus on a specific problem: the scope of HF-RPA and the *raison d'être* of SRPA – and eventually other extensions.

There are two reasons to go beyond HF-RPA and consider SRPA. They are respectively connected to two ways to view RPA and eventually to the treatment of the nuclear force.

View 1: Linear-response theory

HF-RPA has been shown to be the linear limit of time-dependent HF. It is therefore the natural starting point for a linear-response theory of the nucleus, and in particular of collective vibrations. SRPA then plays a complementary role, from a phenomenological point of view: it is introduced as a linear response theory with collision terms, with the purpose of describing collisional damping of collective excitations [34, 35]. The nuclear interaction is of secondary consideration here. That said, we should note that effective interactions that have been tailored to the mean field are, in principle, not suitable for application to SRPA. The first reason is the double-counting of $2p$-$2h$ effects: once implicitly, by the interaction's fitted parameters, and once more explicitly, by SRPA. The second reason is specific to zero-range effective interactions, namely Skyrme-type interactions, with no natural momentum cutoff. Both problems are currently resolved in practice [45] by means of the so-called subtraction method [46].

View 2: Perturbative expansions in many-body theory
RPA theories represent classes of correlations beyond the mean-field level. In the context of nuclear collective excitations, the utility of SRPA is apparent when we consider the application of realistic, unitarily transformed nuclear Hamiltonians [23], which have not been tailored to the mean-field level. Such Hamiltonians are rendered to a large extent perturbative by their prediagonalization. However, they are not necessarily tailored to the simplest model spaces (HF, RPA); in other words, their perturbative nature does not necessarily entail convergence of the perturbation series at zeroth order. SRPA is then viewed as the second-order extension on the path to convergence in the description of excited states.

It is in this spirit of searching, in effect, the convergence of a perturbation series that HF, RPA, and SRPA were sequentially explored with input from realistic NN(N) Hamiltonians in the recent past [38, 47-56]. We review some of the related activity and lessons in the following section.

HF-(S)RPA WITH REALISTIC INTERACTIONS

We begin our survey with an application of the UCOM Hamiltonian and SRG-evolved Hamiltonians to HF and perturbation-theory calculations of nuclear ground states. UCOM stands for *unitary correlation operator method* and SRG stands for *similarity renormalization group*. The UCOM Hamiltonian is a two-nucleon Hamiltonian obtained from the ArgonneV18 potential by means of a similarity transformation. The unitary operator defining the transformation encodes short-range central and tensor correlations, which henceforth are imprinted onto the Hamiltonian and need not be encoded in the many-body state. The parameters of the transformation are adjusted to the energies of 3 and 4-nucleon systems and thus presumed to optimally minimize the net contribution of transformation-induced and of “genuine” three-body forces. SRG Hamiltonians are obtained from realistic or chiral potentials by solving flow equations with respect to the kinetic-energy operator and to various cutoff protocols and flow parameters. The idea is to achieve a prediagonalization of the Hamiltonian in momentum space. For more details see [23].

Let us summarize the findings. Within UCOM-HF [47] all examined closed-shell nuclei were found under-bound by approximately the same amount, namely 4 MeV per nucleon, and were somewhat too small and dense, as judged by their small charge radii. The inclusion of second order corrections within perturbation theory brings the energies closer to the empirical values, while higher orders in the series have minimal effects, thus signifying a convergence of the expansion.

Typical SRG-evolved Hamiltonians similarly applied lead to increasingly over-bound heavy nuclei, eventually collapsing to highly dense systems. Since HF is a variational approach, additional correlations could only reduce the energy further, i.e., they could not resolve this problem. A combination of UCOM and SRG methods improved results [50]. Charge radii remained consistently underestimated in all approaches signifying an irreducible 3N effect. The results can be reasonably reconciled with nature with the inclusion of only a moderate phenomenological three-nucleon correction to the Hamiltonian [50, 51].

To bring the above results into perspective, let us consider a) the finely tuned nature of nuclear saturation and b) the relative weakness of the aforementioned 3N correction.

Nuclear saturation point
The energy per particle of symmetric nuclear matter as a function of the density ρ reaches its minimum at a density ρ_0 of about 0.16fm^{-3} with a value E_0 of about -16MeV. It is the result of the difference of two comparable quantities: the corresponding free-fermion kinetic energy, which equals $(3/5)(\hbar^2/2m)k_F^2$ (m is the nucleon mass and k_F is the Fermi momentum), and the potential energy. Some typical curves are shown in Fig. 1. Specifically, the thick red line depicts a realistic EoS for symmetric nuclear matter modeled here as a KIDS-EoS [12]: it consists of the free kinetic energy (blue dotted line) and the potential energy (thick green line), expressed as an expansion in powers of k_F. There are three potential-energy terms used here, corresponding to the parameter set KIDS-ad2 [12]. The thin green line shows a slightly deviating potential energy curve (approximate potential energy), obtained here for illustration purposes by arbitrarily scaling each of the three potential terms by a factor 0.7-

0.8. Added to the free kinetic energy, it leads to the EoS depicted with the thin red line.

It is plain to see that even a small error in the knowledge of the potential energy, be it owing to an imprecise knowledge of the nuclear interactions or the incomplete inclusion of correlations (which are interrelated effects), can lead to a saturation point well removed for the empirical regime and corresponding to highly dense or dilute or over/under-bound nuclei.

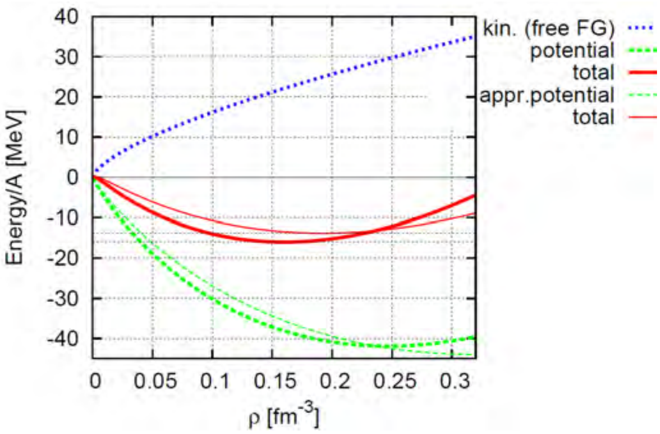

Fig. 1: The thick red line depicts a realistic EoS for symmetric nuclear matter and the thick green line the contribution of potential energy, once the free kinetic energy (blue dotted line) is subtracted. The thin green line shows a slightly deviating potential energy curve (approximate potential - see text), leading, however, to a saturation point widely removed from the empirical regime (thin red line).

3N correction

In the context of phenomenological energy-density functionals, density-dependent "interactions" (DDI) are introduced to take into account 3N forces and to encode correlations beyond the mean field. Without DDIs, nuclear ground states collapse to enormous densities and no physical solutions can be obtained. On the other hand, in the case of UCOM and SRG evolved interactions, the 3N term, when introduced, can be considered merely a correction. It is necessary for improving the saturation point, but it is roughly one order of magnitude weaker than the typical phenomenological DDI. If we compare the corrective terms of Ref. [51] with the DDI of the Gogny interaction, for example, we have:

$$t_3\,(\text{UCOM-SRG})\cdot\rho_0 : \; t_3\,(\text{D1S})\cdot\rho_0^{\alpha} \approx 0.08$$

Such is roughly the error we make in ignoring the 3N.

Let us then, for the moment, accept that the missing 3N effects are weak and proceed to some results of HF-(S)RPA using the UCOM interaction.

HF-(S)RPA was applied to closed-shell nuclei ^{16}O, ^{40}Ca, and ^{90}Zr [49] and eventually other nuclei. The main conclusions were as follows.

Fragmentation and energetic shift

The energies of the collective states are lower (by several MeV) in SRPA than in RPA. The working interpretation is that the coupling to $2p$-$2h$ configurations dresses the in-medium nucleon propagators, leading to a denser single-particle spectrum and overall lower energies. An example of how this works is illustrated in Fig. 2. Here, the contribution of a specific ph configuration, namely proton $1s_{1/2}$ to $1d_{5/2}$, to the quadrupole transition strength of ^{40}Ca is shown. In the HF approximation (bottom), obviously all spectroscopic strength is concentrated on one peak, at an energy equal to the HF energies of the particle and the hole states. In RPA some fragmentation is observed. In SRPA (top) the fragmentation is stronger (notice the scale) and spans a broader energy regime.

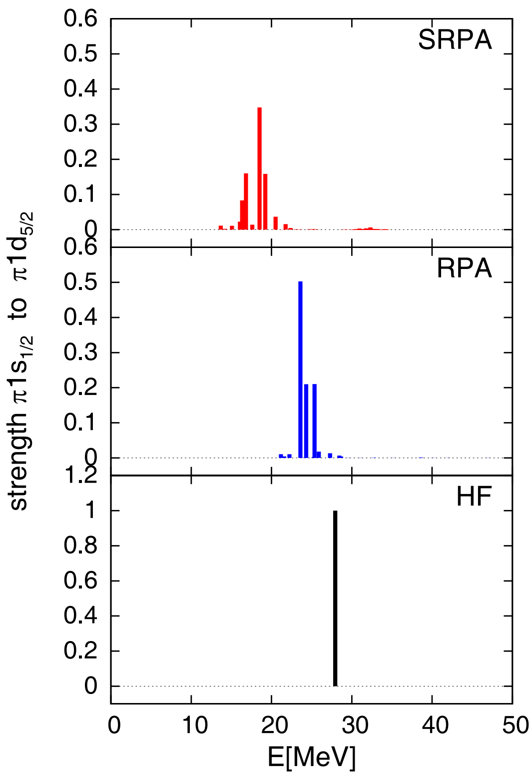

Fig. 2: Strength of a *ph* configuration contributing to the quadrupole response of ^{40}Ca. Compared with HF (bottom) and to RPA (middle), we observe fragmentation and lowering of the energy when coupling to 2*p*-2*h* configuration is introduced within SRPA.

Also noticeable is the shift of the centroid to lower energies corresponding, as mentioned, to a compression of the single-particle spectrum.

Dipole and quadrupole response

The GDR and GQR energies are found to be overestimated by RPA but can be corrected by SRPA toward the empirical values [49]. The results represented an early success of correlated realistic interactions in collective phenomena and a justification for going to the second order within RPA, i.e., the next step in the perturbation series. The HF-SRPA combined with UCOM found an early application in interpreting the fine structure of the giant quadrupole resonance of ^{40}Ca observed at proton scattering experiments at iThemba LABS [52]. Other applications have followed [53, 54].

Despite the promising results for the GDR, application of UCOM in the region of the isoscalar low-energy dipole mode and of pygmy resonances both in RPA and SRPA leads to overly strong isovector transitions as documented in the case of ^{48}Ca [55]. These results are typically attributed to excessive surface neutrons. Phenomenological 3N corrections were found unable to correct this effect. It is interesting, then, to observe that chiral NN+NNN interactions provide very good results [56].

Monopole response

The energy of GMR, well reproduced by HF-RPA (perhaps by accident), is obtained at very low energy within HF-SRPA [49]. This may not be surprising given that the GMR energy is determined by the curvature of the EoS with respect to the density, which is depicted in Fig. 1, and is highly sensitive to missing 3N effects. It could also be argued that the SPRA instabilities are at play and affect especially the GMR, because it has the same quantum numbers as the ground state. In this spirit, the subtraction method can be applied as a remedy in order to proceed, for example, to studies of dissipation mechanisms.

In Fig. 3 we show an application to the monopole response of ^{40}Ca. The unsurprising result is that the energies of the peaks are not dramatically shifted with respect to RPA. The notable result is that any fragmentation observed due to $2p$-$2h$ configurations is only activated at high energies, i.e., there is no internal damping in this approach. The results of course could be different if we considered a correlated reference state, instead of HF, which would open more channels for energy dissipation.

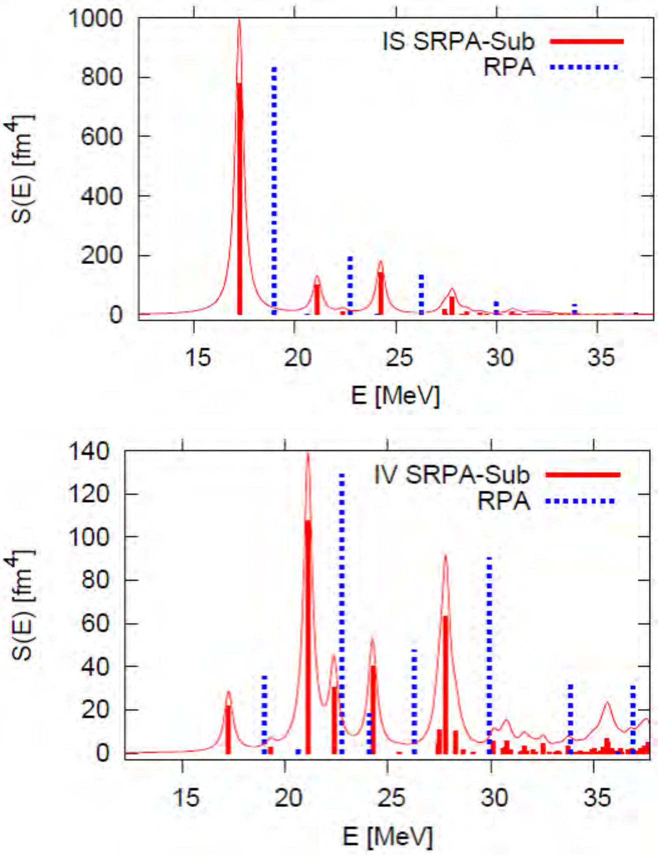

Fig.3: Isoscalar (top) and isovector (bottom) monopole spectrum of ^{40}Ca. Red bars: HF-SRPA with subtraction; the continuous red line represents the same transition strength distribution but smoothened with a Lorenzian curve for visualization. Blue bars: HF-RPA. The fragmentation effect of SRPA, visible in the IV channel but present in both, is observed at energies beyond the GMR in the present case where the UCOM Hamiltonian is used.

Let us note that the results would likely be different in applications with effective "interactions" where the HF particles are already, effectively, dressed. The question then becomes that of double counting mentioned above.

Thus, ground-state correlations serve not only the practical purpose of stabilizing the ground state, but also a physical purpose and may potentially be observable. It remains to be seen whether they play any role in this particular case. On the other hand, strength quenching of magnetic and Gamow-Teller transitions owing to ground-state correlations have been previously documented [35].

SUMMARY

The lesson to take from the above article can be summarized as follows: the matching between the quantum many-body method and the nuclear Hamiltonian is like digging a railway tunnel from either side of a mountain; the two ends must meet seamlessly, or the train will derail.

We considered collective vibrational modes in the linear-response regime because they open a window to the nuclear EoS. First-order, particle-hole RPA is the par excellence tool of linear response theory. However, no suitable, well defined nuclear Hamiltonian seems to exist for its application. Instead, density-dependent interactions, defined in the context of nuclear DFT (not the other way around) and already encoding in-medium correlations, are demonstrably excellent companions.

It may be possible to realize an extended version of RPA with a realistic Hamiltonian, thus taking the "second view" of RPA introduced earlier. HF-SRPA is not the most suitable method, because of its inherent inconsistencies. However, other candidates are under development.

Two-nucleon Hamiltonians generally fail to generate the correct saturation point. In many cases, correlations are not the answer: nuclei are predicted over-bound within the simple variational HF approximation. Three-nucleon interactions or proxies thereof seem inescapable. They are of course interrelated with and depend upon the two-nucleon interaction they accompany. See also related discussions within the chiral EFT program, Ref. [24].

The effect of taking into account a three-nucleon interaction may be as simple as correcting the saturation point (Fig. 1) or as surprising as pushing the neutrons to their rightful place (see, e.g., [56] – it is, however, an open-ended result).

The above are examples of the non-trivial interplay of correlations and interactions, and we anticipate further surprises down the road. Regarding the focus of this article, it is hoped that an *ab initio* program will be able to reveal the dissipation mechanisms in the nuclear medium and to dissect the low-lying spectrum of surface vibrations. Both are likely influenced by short-range correlations whose modeling remains in an uncertain position. Ongoing experimental activity and new developments on the theory frontier will set the stage for new discoveries in the near future.

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