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Infinite matter properties and zero-range limit of non-relativistic finite-range interactions

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ABSTRACT

We discuss some infinite matter properties of two finite-range interactions widely used for nuclear structure calculations, namely Gogny and M3Y interactions. We show that some useful informations can be deduced for the central, tensor and spin–orbit terms from the spin–isospin channels and the partial wave decomposition of the symmetric nuclear matter equation of state. We show in particular that the central part of the Gogny interaction should benefit from the introduction of a third Gaussian and the tensor parameters of both interactions can be deduced from special combinations of partial waves. We also discuss the fact that the spin–orbit of the M3Y interaction is not compatible with local gauge invariance. Finally, we show that the zero-range limit of both families of interactions coincides with the specific form of the zero-range Skyrme interaction extended to higher momentum orders and we emphasize from this analogy its benefits.

1. Introduction

The nuclear energy density functional theory (NEDF) is the tool of choice for the description of nuclear properties from drip-line to drip-line and from light to super-heavy elements [1]. Among the

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different choices for the functional, the most popular are the ones derived from the non-relativistic effective nucleon–nucleon interactions as the zero-range Skyrme [2,3], and the finite-range Gogny [4,5] or M3Y [6,7] families. At the mean field level, the global performances along the nuclear chart are comparable both for ground states [8,9] and excited ones [10,11] and there is no clear argument, from this perspective, to prefer a zero-range or a finite-range interaction.

In this article, we aim to further analyze the aforementioned effective interactions by comparing their results in infinite nuclear matter. Although the infinite medium is an idealized system, its equation of state, and more particularly its part around saturation density, represents a very important constraint not only for phenomenological interactions [12], but also for microscopic calculations based on bare nucleon–nucleon interactions. We propose here to compare some results obtained from calculations based on the previous phenomenological effective interactions with microscopic calculations based on the bare nucleon–nucleon interaction, as Brueckner–Hartree–Fock (BHF) [13], Chiral Effective Field Theory (χ-EFT) [14,15], or Many Body Perturbation theory (MBPT) [16,17]. These microscopic results represent a very useful input to determine those parts of the effective interactions which are difficult to fix in the standard fitting procedure based on finite nuclei properties.

Thus, besides comparing the symmetric nuclear matter (SNM) equation of state (EoS), we also consider its separate contributions, as its decomposition in spin–isospin (S, T) channels or in partial waves. Comparing such contributions leads to additional constraints providing further insights on those effective interaction terms which do not appear explicitly in the EoS, as the spin–orbit and tensor interaction terms [18]. One of the goals of this work is to show that it is possible, using a partial wave decomposition of the EoS, to give an alternative view of the main characteristics and limitations of these potentials. In that sense, this study is complementary, to other analysis done in finite nuclei [19–21] regarding tensor terms. Whereas all the microscopic calculations are in quite reasonable agreement at saturation density and in the low-density region [22], presently only the Brueckner–Hartree–Fock calculations [13] provide us with all partial waves contributions to the EoS in a wide density range. For this reason, BHF results are used to constrain the spin–orbit and tensor terms of effective interactions. It is however implicit that the method proposed in this article would also hold if some other microscopic results were available and used.

The bare nucleon–nucleon interaction contains an important tensor part, which is necessary to reproduce not only the phase shifts of the nucleon–nucleon scattering, but also the quadrupole moment of the deuteron. However, apart from some exploratory studies [23,24], these terms have been omitted in the study of finite nuclei up to recently. In general, the inclusion of tensor terms allows for a better description of the evolution of nuclear shells for stable nuclei as well as exotic ones. Furthermore, it has received a particular attention in the recent years due to its contribution to the shell evolution in atomic nuclei [25]. Nowadays there are several zero- and finite-range effective interactions containing tensor terms. Among the finite-range ones, let us mention the M3Y type effective interaction by Nakada [7,26,27], which includes finite-range spin–orbit and tensor terms, whose parameters are fitted to the Brueckner's G-matrix based on a bare interaction. Much closer to the spirit of an effective interaction, a tensor term was added to a Gogny-type potential to describe the evolution of nuclear shells for exotic nuclei as well as stable ones [20,28]. Concerning Skyrme interactions, zero-range tensor terms as originally proposed by Skyrme have been either included perturbatively to existing central ones or with a complete refit of the parameters [19]. For a general discussion see Ref. [29], where a systematic study of the zero-range effective tensor interaction combined with a standard Skyrme interaction has been made.

The link between zero and finite-range interactions is the object of some debate. In this article we contribute to it, trying in particular to show how a zero-range interaction can constitute a reliable approximation of a finite-range one. This leads us to consider the next-to-next-to-next to leading order momentum expansion of the Skyrme pseudo-potential [30,31] which represents an extension of the standard Skyrme model [2,32]. It is currently referred to as N3LO Skyrme pseudo-potential, a term introduced in Refs. [30,31] in analogy with expansion techniques employed in chiral effective field theory methods. The role of the higher order gradients in N3LO is to mimic the effect of a range with higher and higher accuracy (in agreement with Ref. [33] in the context of the Density Matrix Expansion). In this respect, we have obtained the N3LO zero-range limit of the Gogny and M3Y interactions. Thanks to the analytical properties of the infinite nuclear medium, we will show that