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Review

Tensor interaction in mean-field and density functional theory approaches to nuclear structure

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ABSTRACT

The importance of the tensor force for nuclear structure has been recognized long ago. Recently, the interest for this topic has been revived by the study of the evolution of nuclear properties far from the stability line. However, in the context of the effective theories that describe medium-heavy nuclei, the role of the tensor force is still debated. This review focuses on ground-state properties like masses and deformation, on single-particle states, and on excited vibrational and rotational modes. The goal is to assess which properties, if any, can bring clear signatures of the tensor force within the mean-field or density functional theory framework. It will be concluded that, while evidences for a clear neutron–proton tensor force exist despite quantitative uncertainties, the role of the tensor force among equal particles is less well established.

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1. Introduction

As discussed in all nuclear physics textbooks, the tensor force is one of the important components of the nucleon–nucleon (NN) interaction. The long-range part of this interaction is associated with the exchange of the lightest meson, namely the pion, and it has a tensor character; the one pion exchange potential (OPEP) is the most well known part of the NN interaction and yet at the same time it is not strong enough to bind two nucleons, because its expectation value is of the same order of magnitude of the kinetic energy associated with the relative motion. However, the tensor force is of paramount importance for the nuclear binding since the exchange of two pions, i.e., the second order effect of the tensor force, is providing a strong central attraction in the isospin zero ($T = 0$) channel which is responsible for the deuteron binding. At the same time, the electric quadrupole moment of the deuteron is a signature of the pure tensor component. The introduction of the tensor force dates back to the early 1940s [1–3], not so long after the birth of nuclear physics (see also [4]).

All this belongs to conventional nuclear physics wisdom. More qualitative and especially quantitative understanding has been obtained later concerning the role of tensor terms in the bare NN interaction, since sophisticated interactions have been built that can explain at the same time the deuteron and many high-precision scattering data with a χ^2/datum of the order of $\approx$1. This can be done within the traditional picture of the NN force and, to some extent, also within effective field theories (EFTs) based on the chiral symmetry and its breaking (see, e.g., [5] for recent reviews).

However, our focus is different and concerns the role of tensor terms when the interaction in the nuclear medium is considered, in particular within the framework of those models that can be applied throughout the whole periodic table like self-consistent mean-field or density functional theory (DFT) based methods [6]. There is a new blooming of studies of the possible tensor terms, in general because of the tremendous progress achieved by these theoretical methods in the last decades but also for specific reasons that we shall briefly illustrate.

A very important motivation to revive the study of the tensor force in nuclear physics is related to the new domain of exotic, unstable nuclei. Generally speaking, nuclei far from the stability valley open a new test ground for nuclear models. Recently, many experimental and theoretical efforts have been devoted to the study of the structure and the reaction mechanisms in nuclei near the drip lines. Modern radioactive ion beam facilities (RIBFs) and experimental detectors reveal several unexpected phenomena in unstable nuclei such as the existence of haloes and skins [7], the modifications of shell closures [8] and the so-called pygmy resonances in electric dipole transitions [9]. The tensor force plays a role, in particular, in the shell evolution of nuclei far from the stability line [10]. This fact has motivated thoroughly studies of the effect of the tensor force on the shell structure of both stable and unstable nuclei, with emphasis also on masses, single-particle states and sometimes on the onset of deformation.

Another context in which the tensor force is expected to be crucial are the properties of spin and spin–isospin states. Such modes of nuclear excitation, like the Gamow–Teller or spin–dipole states, are not only of interest for nuclear structure but also for nuclear astrophysics and particle physics (in connection with β and $\beta\beta$ decays, neutrino mass and its possible Majorana nature). Review papers have been devoted to this topic [11,12]. Many of the currently employed mean-field or DFT-based methods are not well calibrated in the spin–isospin channel and/or suffer from spin and spin–isospin instabilities (i.e., spontaneous magnetization) above some critical density (see, e.g., [13] and references therein). There is obviously a strong need to improve the predictive power of the models as far as the spin–isospin states are concerned, and it must be established to which extent the tensor terms are important in this channel.

Our review is somehow timely because most of this discussion concerning the tensor force in stable and unstable nuclei, and its role for collective excitations (mainly spin and spin–isospin modes but also density modes and rotations of deformed nuclei), has already produced a considerable number of results, and yet some of the key questions are not completely solved.

One of the fundamental issues is related to whether the effective tensor force that governs shell evolution and excited states in complex nuclei keeps a close resemblance with the original bare tensor force or not. In some of the works that we shall discuss, the adopted point of view is that at least the proton–neutron tensor force is only slightly renormalized in the nuclear medium because of its long-range character; in other words, some authors believe that finite nuclei still bear signatures of the tail of the OPEP. In other cases it is assumed that the potential is actually renormalized but the bare OPEP (together with the tensor components associated with exchange of other mesons) still must be taken as guideline. Another, complementary point of view is that in the mean-field or DFT description the effective interaction does not need to bear any connection with the interaction in the vacuum. When its parameters are fitted, the effect of the bare tensor force is likely