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Tensor optimized antisymmetrized molecular dynamics for relativistic nuclear matter

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ABSTRACT

We apply a newly developed many-body theory, tensor optimized antisymmetrized molecular dynamics (TOAMD), to nuclear matter using a relativistic bare nucleon-nucleon interaction in the relativistic framework. It becomes evident that the tensor interaction plays an important role in nuclear many-body system due to the role of the pion in a strongly interacting system. We take the relativistic nuclear matter (RNM) wave function as a basic state and add tensor and short-range correlation operators in the form of pion and omega-meson correlation functions acting on the RNM wave function using the concept of TOAMD. We use the Monte Carlo (Metropolis) method based on the Gaussian integration and the second quantization method for antisymmetrization to calculate all the matrix elements of the many-body Hamiltonian. We write the whole formula of the TOAMD method for numerical calculations of the nuclear binding and saturation properties of nuclear matter using one-boson exchange potential.

1. Introduction

It is very important to describe nuclear many-body system using the bare nucleon-nucleon (NN) interaction. The NN interaction has a strong tensor force due to the pion exchange and a strong short-range repulsion due to the quark structure of the nucleon. These two features are important to determine the structure of the deuteron made of a proton and a neutron. We are able to solve the two-body system using the Schroedinger equation. The resulting *S*-wave component has a strong depletion in the central region due to the repulsion and the *D*-wave component has large momentum components [1]. The central force is not enough to bind the deuteron and the tensor force provides the dominant attraction through the coupling of the *S*- and *D*-wave components. It is definitely necessary to develop a theoretical framework to include these features in the many-body wave function for complex nuclei. They were treated in a few-body framework for *S*-shell nuclei as ^{3}He and ^{4}He by explicitly minimizing the total energy of few-body variational wave functions. It was demonstrated that these two features are absolutely important for the structures of *S*-shell nuclei [2]. However, it is difficult to go beyond the *S*-shell nuclei in the few-body framework due to the difficulty to treat antisymmetrization.

The Argonne group developed the Green's Function Monte Carlo (GFMC) method to treat heavier nuclei including *P*-shell nuclei [3]. They were able to solve many-body systems using the NN interaction and additionally the three-body interaction

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through Δ excitation. They found the importance of the role of pion exchange for the binding energy of nuclei. Hence, it is very important to treat the pion exchange interaction, where the difficulty of the many-body calculation lies on the treatment of the tensor force. At the present, they are able to extend their calculations to heavy nuclei as the ground state and the Hoyle state of ^{12}C [4]. The difficulty to go beyond this nucleus in the GFMC method comes from the limitation of the computer resources. As an effort to reduce the demand on the computational resources, we introduced the tensor optimized shell model (TOSM) to treat the tensor correlation [5]. In addition to the shell model state, we include two-particle two-hole ($2p2h$) states in order to allow the tensor force to have large matrix elements. TOSM is successful to describe shell model states in light nuclei, but it does not provide enough binding energy for cluster states [6]. Following the success of TOSM, a powerful theoretical framework was constructed by combining TOSM and the antisymmetrized molecular dynamics (AMD) so as to treat the cluster structures [7]. This combined framework was named as tensor optimized antisymmetrized molecular dynamics (TOAMD), where the antisymmetrization was treated in the momentum space and all the matrix elements were calculated by the analytical gaussian integration method.

As for nuclear matter, the Brueckner–Hartree–Fock (BHF) calculation of nuclear matter was performed by Brockmann and Machleidt in the relativistic framework [8]. They used the meson exchange interaction (Bonn potential) for the NN interaction, and showed that the relativistic effect had a strongly repulsive effect at higher densities and the saturation point was shifted to a reasonable density. Hence, it is important to use the relativistic kinematics for the study of nuclear matter.

In the non-relativistic framework, Akmal, Pandharipande and Ravenhall studied nuclear matter using the variational chain summation (VCS) method [9]. They had to include the three-body repulsive interaction and the boost effect caused by the relativistic kinematics. Including further the three-body interaction through the Δ excitation, they could get reasonable equations of state (EOS) for symmetric and pure neutron matter.

Recently Hu, Toki and Ogawa applied the TOSM method for the calculation of nuclear matter in the relativistic framework [10]. Using Bonn-B potential they obtained the EOS of nuclear matter at a reasonable density. However, the binding energy was about 5 MeV short from the empirical value. This amount should be attributed to the three-body interaction through the Δ excitation. This is the motivation of the present work to apply the TOAMD framework to nuclear matter, since the inclusion of the three-body interaction is straightforward in TOAMD.

In this paper, we apply the TOAMD framework to the formulation of the relativistic nuclear matter. The basic wave function of nuclear matter is simple because the momentum is a good quantum number and the spin space is saturated. The momentum states are occupied by nucleons up to the Fermi surface. The application of the tensor and short-range correlations makes the wave function to have the realistic features. The correlation functions contain variational parameters to be fixed by the energy minimization.

Section 2 provides the basic ingredient of the new formulation TOAMD for relativistic nuclear matter. Section 3 provides the calculation method of the matrix elements with short-range and tensor correlations. In Section 4, we write various useful tools to calculate the matrix elements of multi-body terms in the RNM wave function. Section 5 is devoted to the summary of this paper. We add few appendices to elucidate the details of formulations.

2. Tensor optimized antisymmetrized molecular dynamics for relativistic nuclear matter

We write here the basic idea of the tensor optimized relativistic nuclear matter (TORNM) theory, which is a straightforward application of TOAMD developed for finite nuclei to nuclear matter [7]. We write all the ingredients in this section as TORNM wave function, Hamiltonian and the matrix elements of the Hamiltonian based on the RNM wave function.

2.1. Wave function of TORNM

In this subsection, we introduce the TORNM wave function for nuclear matter. In the framework of the tensor optimized shell model (TOSM), it is important to prepare a basic wave function to represent a correct ground state profile with low momentum components, and add high momentum components excited by the strong tensor interaction [5]. In TOSM, the high momentum components are introduced in terms of $2p2h$ excitations from the low momentum components [5]. Instead of the $2p2h$ excitations of the TOSM, we introduce the short-range and tensor correlation operators applied to the RNM wave function in the TOAMD framework [7]:

$$\begin{aligned} |\Psi\rangle &= (1+F_S)(1+F_D)|RNM\rangle \\ &= (1+F_D+F_S+F_SF_D)|RNM\rangle. \end{aligned} \tag{1}$$

Here, $|RNM\rangle$ describes nucleons in the Fermi sea with low momentum components and $F_S|RNM\rangle$ represents high momentum states made by the short-range correlation operator F_S. $F_D|RNM\rangle$ represents high momentum states made by the tensor correlation operator F_D on the basic RNM wave function. The state $F_SF_D|RNM\rangle$ should represent interference terms of the short-range and tensor correlations. In principle, we can add more correlation operators to the above wave function to get energetically most favorable ground state. The correlation operators F_S and F_D contain variational parameters to be fixed by the energy minimization.

$|RNM\rangle$ is a RNM wave function for infinite matter:

$$|RNM\rangle = \mathcal{A}\,\Pi_{i=1}^{A}\psi_{p_i}(\vec{r}_i)\xi_{p_i}(t_i), \tag{2}$$