Study of nuclear structure with $NN$-interaction in low momentum-space: a new treatment of short-range and tensor correlations

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Abstract. We develop a new type of effective interaction to use in a model-space calculation of finite nuclei. We start with a realistic $NN$-potential and reduce its model-space with the use of a unitary transformation thereby obtaining the effective $NN$-potential. We choose the unitary operator to eliminate the hardcore in the central force and to keep the tensor force essentially invariant. We expect that the tensor force can be taken into account to a good extent by using a parity-mixed single-particle state in a model-space calculation.

A construction of an effective interaction for a given model-space has been an important subject in nuclear physics. There are many effective interactions, such as the G-matrix and the Volkov force, which have been conventionally used. Many of them do not include the hardcore of the nuclear force. The tensor force is not considered explicitly also and its effect has been renormalized into central and spin-orbit terms of the effective interactions. However, these conventional effective interactions have a serious problem that the obtained nuclear structure is not necessarily based on a realistic nuclear force. Now we are in a stage to develop a new type of effective interaction because of the following observation. Recently, we have seen an important development in the nuclear structure study based on model-space calculations; a serious treatment of the tensor correlation using a configuration mixing.$^{[1, 2]}$ We can study the correlation in a physically transparent manner by describing nuclei in a model-space. Besides, we learned that a next-generation effective interaction may include the tensor force explicitly because we have seen that the tensor force is well handled in an appropriate model-space. Thus we may just eliminate the hardcore of the nuclear force; we may left the tensor force unchanged.

The purpose of this work is to start with a realistic nuclear force and construct the corresponding effective interaction which meets this current situation. Note that we will restrict ourselves to only two-nucleon force.

We start with the Schrödinger equation, $H \Psi = E \Psi$, with $H = T + V_C + V_T$; $T$, $V_C$, and $V_T$ are the kinetic term, the central force and the tensor force, respectively. The hardcore is involved in $V_C$. Then we transform $H$ with the use of a unitary operator $U$ to obtain the resulting equation, $U^\dagger H U \tilde{\Psi} = E \tilde{\Psi}$ with $\tilde{\Psi} = U^\dagger \Psi$. We need to use the operator $U$ which generates the effective Hamiltonian, $U^\dagger H U$, without the hardcore. For such an operator, we modify the unitary operator for a low-momentum interaction described in Ref. $^{[3]}$; our operator eliminates high-momentum components of the central force. The procedure is as follows.
(i) We transform $T + V_C$ using the unitary operator. We determine the unitary operator so as to decouple the high- and low-momentum components of nucleon states at a given cutoff.

(ii) We transform $T + V_C + V_T$ using the unitary operator determined in the previous step. Following the steps (i) and (ii), we obtain the non-local effective interaction represented in the momentum space ($q$-space). For a practical calculation of nuclear structure, a local $r$-space interaction is preferred. Therefore, we will localize the interaction referring to a proposal in Ref. [4]. We use a localized potential which satisfies the following two conditions.

(a) The localized potential reproduces diagonal components of the non-local $q$-space potential.
(b) The asymptotic behavior of the localized potential reproduces the one-pion-exchange tail.

In Fig. 1, we show the $q$-space effective $NN$-potential obtained in the steps (i) and (ii). We calculated observables (phase-shifts and the deuteron binding energy) with the effective interaction. The obtained observables are the same as those given by the bare interaction as they should. Here, we expect the following two characteristics of the effective interaction. Although the high- and the low-momentum states of the nucleon are decoupled in the step (i), the existence of the tensor force breaks the decoupling. However, we expect that an effect of the breaking is small for an appropriate choice of the cutoff and therefore high-momentum components of the effective central force may be simply omitted. We also expect that the tensor force is essentially unchanged under the unitary transformation in the step (ii). Thus we may replace the effective tensor force with the bare one. We confirmed that the expected characteristics are indeed well realized. We make use of the characteristics and derive the corresponding localized $r$-space effective interaction shown in Fig. 2. The hardcore is largely reduced and the intermediate attraction becomes shallow as expected. We confirmed that this local potential reproduces the two-nucleon observables to a good extent. In future, we will examine how well this effective local interaction describes few-nucleon systems.

References
[1] Sugimoto S, Ikeda K and Toki H 2004 *Nucl. Phys.* A740 77
[2] Myo T, Kato K and Ikeda K 2004 *Preprint* nucl-th/0411086
[3] Epelbaum E, Glöckle W, Krüger A and Meißen U-G 1999 *Nucl. Phys.* A645 413
[4] Sprung D W L and Banerjee P K 1971 *Nucl. Phys.* A168 273