Strongly tensor correlated Hartree-Fock theory

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We formulate a nuclear many-body theory for large mass nuclei (A $\geq$ 12) in order to understand basic properties of finite nuclei and nuclear matter as a consequence of the interaction among constituent particles on the same footing as the hadron physics [1, 2]. The nuclear interaction is characterized by strong tensor interaction due to the pion-exchange and short-range repulsive interaction due to quark degrees of freedom in nucleons. The pion plays very important role in both nuclear and hadron physics. To treat properly the role of pions in nuclear physics is a key to make connection between nuclear and hadron physics, where their dynamics is governed by the chiral symmetry in quantum chromodynamics.

We employ the Hartree-Fock method as a starting point of treating large mass nuclei. Since the pion has a pseudo-scalar nature and its intrinsic spin-parity is $J^\pi = 0^-$, the pion-exchange interaction has a strong tensor component. The tensor interaction $S_{12} = [Y_2 \otimes [\vec{\sigma} \otimes \vec{\sigma}]_2]_0$ has a spherical harmonics $Y_2(\hat{r})$ and spin-flip operators with rank 2. The tensor interaction causes space and spin transitions by $\Delta L = 2$ and $\Delta S = 2$, respectively and it cannot be described properly in the spin saturated Hartree-Fock (HF) space. On the other hand, transition matrix elements from the HF state to excited states by the tensor interaction provide the dominant contributions to the binding energies in light nuclei. Hence, we have to extend the HF $(0p - 0h)$ model space at least to $2p - 2h$ excitations $|2p - 2h; \alpha\rangle$ so as to express the effect of the tensor correlation with the high momentum components,

$$|\Psi\rangle = C_0|\mathrm{HF}\rangle + \sum_\alpha C_\alpha |2p - 2h; \alpha\rangle. \quad (1)$$

We take summation of all the possible $2p-2h$ configurations labeled by α with higher pionic angular momentum $(0^- \otimes L^{(-1)^L})$ of exchanged pion until the total energy convergence is realized. This is a trial wave function for energy variation, $\delta\langle\Psi|\hat{H} - E|\Psi\rangle = 0$, to handle the strong tensor interaction.

We take a variational principle for the ground state wave function. The variational parameters are 1: the amplitudes of the 2p-2h states C_α, 2: the single-particle states in the Fermi-sea and 3: the correlation function for taming the short-range repulsion are decided by energy minimization. An original point of this theory is that the single-particle states in the Fermi-sea are obtained self-consistently under the effect of those two characteristic tensor and short-ranged repulsive correlations. Those two equations of motion from variations 1 and 2 are solved iteratively until a self-consistency is realized.

We elucidate the nature of this theory by comparing with the G-matrix in the Brueckner-Hartree-Fock (BHF) theory [3]. We can derive an effective Hamiltonian from two coupled equations of 1 and 2. We write an expectation value of the HF state $|0\rangle$ as follows [1, 2],

$$\langle 0|H_{eff}|0\rangle = |C_0|^2 \Big\{ \langle 0|\hat{T} + \hat{V}|0\rangle - \sum_{\alpha\beta} \langle 0|\hat{V}|\alpha\rangle \frac{1}{\langle\beta|\hat{H} - E|\alpha\rangle} \langle\beta|\hat{V}|0\rangle \Big\}. \quad (2)$$

Here, we abbreviate $|2p - 2h; \alpha\rangle = |\alpha\rangle$.

An important feature of this theory is that the part of the HF space cannot be normalized. It means that the amounts of the low momentum components (HF) are reduced ($|C_0|^2 \neq 1$), and some probabilities for high momentum components caused by the tensor force and short-range repulsion are given ($|C_0|^2 + \sum_\alpha |C_\alpha|^2 = 1$). The second is that the concept of the total energy E of the system appears in the energy denominator in this theory, since we solve a nuclear many-body system as a variational problem. The third is the two-body interaction matrix in $2p - 2h$ states $\langle\alpha|\hat{V}|\beta\rangle$ includes many terms. We have interaction between a particle (hole) in $2p - 2h$ states and a hole in the Fermi-sea in the two-body interaction matrix. Furthermore, we have interactions between particle-particle, hole-hole and particle-hole states in $2p - 2h$ states. Especially the particle-hole interaction produces many body correlations, because any amount of constituent particles of the system can participate to interact in succession even under the restriction of $2p-2h$ excitations in the variational wave function. Therefore, we can treat many-particle correlations within two-body interaction. We are now applying this theory to finite nuclei with Bonn-potential as a realistic nucleon-nucleon interaction.

References

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