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Deuteron-Ξ correlation function studied with three-body model

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Summary. — Many-baryon forces play a crucial role in shaping the structure and dynamics of many-baryon systems. Utilizing three-body correlation functions in femtoscopy offers a promising tool for probing three-baryon forces. However, the dynamics of three-body systems necessary for obtaining these correlation functions remains incompletely understood. In this study, we employ the continuum-discretized coupled channels method, a precise and cost-effective three-body model, to explore the influence of deuteron excitation to its continuum states on the deuteron-Ξ correlation function. Our findings reveal that the deuteron-Ξ interaction derived from lattice quantum chromodynamics does not yield a bound state. Moreover, we determine that the effect of deuteron excitation leads to less than a 10% increase in the correlation function, suggesting the predominance of direct deuteron formation through heavy-ion collisions. Overall, our work lays the groundwork for further investigations aimed at elucidating many-baryon forces.

1. – Introduction

Three-baryon forces are a key to microscopically understand many-baryon systems in terms of their interaction. As regards three-nucleon forces, few-nucleon systems offer an opportunity to access their fundamental information, such as the low-energy constants [1-3] of the chiral effective field theory [4-8]. In contrast, the three-nucleon force in many-nucleon systems has attracted much attention since its impacts is drastic as evidenced by, for example, the spin-parity inversion of the ^{10}B spectra [9], the spin-orbit splitting [10-17], the drip-line determination of oxygen isotopes [10, 15, 18], the explanation for masses and spectroscopy of medium-heavy nuclei [14, 19-21], and the saturation of nuclear matter [22-24].

† Deceased.

The importance of many-baryon force is not limited to nucleon systems but also those with hyperons. Indeed, the three-baryon force among nucleon-nucleon-Λ systems plays a crucial role on accounting for neutron stars that have a mass greater than the two-solar mass [25].

One of the promising tools to study the baryon interaction is the correlation function since it contains the information of the interaction as a scattering wave of systems considered (see eq. (1)). For instance, femtoscopic study of the nucleon-Ξ (Λ-Λ) interaction through the investigation of the proton-Ξ^- correlation function revealed that this interaction is moderately (weakly) attractive, albeit producing no quasibound (bound) states [26].

Similarly, three-baryon interaction could be studied through three-body correlation functions, which were recently observed by the ALICE Collaboration [27]. Also, these data were theoretically analyzed within the hyperspherical harmonics and Faddeev techniques [28, 29]. However, our understanding of the dynamics of three-body systems, pertaining to the three-body correlation functions, remains incomplete. In particular, the formation of the deuteron in the deuteron-hadron correlation function is not clarified as to whether it is due to direct production or final-state interaction [30].

In this study, we investigate the effect of the deuteron dynamical excitation on the deuteron-Ξ^- correlation function to clarify the mechanism of the deuteron formation. Here, the deuteron dynamical excitation stands for the coupled channel among deuteron-Ξ^-, proton-neutron-Ξ^- and neutron-neutron-Ξ^0 channels. This study is a necessary first step towards studying nucleon-nucleon-Ξ interaction, although at the moment we did not include three-body forces in our calculations for simplicity.

2. – Method

We briefly describe our theoretical framework to study the deuteron-Ξ correlation function. See ref. [31] for more complete expression on the method. Following the Koonin–Pratt formula [32, 33], the correlation function is computed by

$$C_{d\Xi}(\boldsymbol{q}) \approx \sum_i \int d\boldsymbol{R}\mathcal{S}(R) \left|\psi_{i0}^{(-)}(\boldsymbol{R})\right|^2, \tag{1}$$

where $\boldsymbol{q}$ and $\boldsymbol{R}$ is the relative momentum and coordinate between the nucleon-nucleon system and Ξ, respectively. The index i specifies the nucleon-nucleon states, as explained below. We adopt the source function $\mathcal{S}$ defined by

$$\mathcal{S}(R) = \left(4\pi b^2\right)^{-3/2} \exp\left[-\frac{R^2}{4b^2}\right], \tag{2}$$

with the source size $b = 1.2$ fm. Note that the results with different source size are relegated to ref. [31]. We assume that $\mathcal{S}$ does not depend on i for simplicity.

The wave function $\psi_{i0}^{(+)}$ describing the relative motion between the nucleon-nucleon system and Ξ is calculated by the continuum-discretized coupled channels method (CDCC) [34-36] as

$$\Psi^{(+)}(\boldsymbol{r}, \boldsymbol{R}) = \sum_i \phi_i(\boldsymbol{r})\psi_{i0}^{(+)}(\boldsymbol{R}). \tag{3}$$

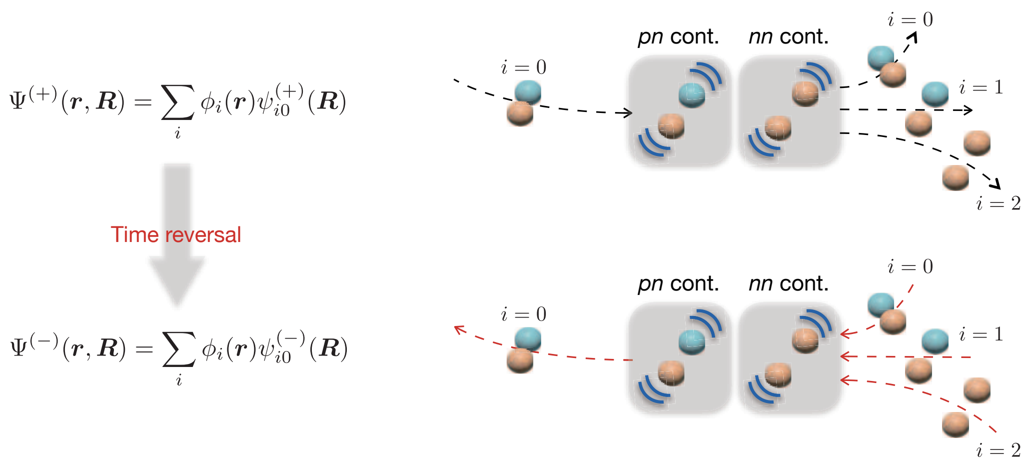

Fig. 1. – Schematic pictures showing the time reversal of the wave function. Within the outgoing boundary condition denoted by the superscript $(+)$, the deuteron exists in the "incident" channel $i = 0$ and various final channels are possible in the "exit" channel. In contrast, within the incoming boundary condition denoted by $(-)$, various scattering states from the source correspond to initial channels, each of which goes to the observed channel $i = 0$. For simplicity we omit the presence of Ξ in the pictures.

Here, $\Psi^{(+)}$ is the total wave function of the three-body system. The nucleon-nucleon relative wave function ϕ_i depends on $\boldsymbol{r}$, the relative distance between two nucleons, and the subscript i identifies the discretized continuum states characterizes energy, spin, and isospin of the nucleon-nucleon system. Also, the subscript 0 stands for the deuteron channel, $i = 0$, which corresponds to the observed channel in the correlation function. The superscript $(+)$ denotes that the wave function satisfies the outgoing boundary condition, and hence, $\psi^{(-)}_{i0}$ satisfying the incoming boundary condition is obtained as the time reversal form of $\psi^{(+)}_{i0}$. The above explanation is schematically shown in fig. 1.

We use the Argonne V4' potential [37] as the nucleon-nucleon interaction, while the potential derived from the Lattice quantum chromodynamics simulation [38] is employed for the nucleon-Ξ interaction. We take into account the nucleon-nucleon continuum states up to around 166 MeV, resulting in the 411 channels in solving the coupled-channels equation.

As mentioned above, this work represents the initial exploration of the deuteron-Ξ^- correlation function within the framework of a three-body model. Therefore, for the sake of simplicity, we impose certain constraints; disregarding three-baryon forces, assuming an i-independent two-body source function, accounting for Coulomb interaction in all isospin channels, considering only s-wave states in all subsystems, presuming isospin symmetry for baryon masses, and neglecting rearrangement channels. The incorporation of these aspects falls within our future research scope.

3. – Results

First, we show the attractive nature of the deuteron-Ξ^- interaction from the correlation function $C_{d\Xi}$ as displayed in fig. 2 as a function of q. The red-solid line is the results

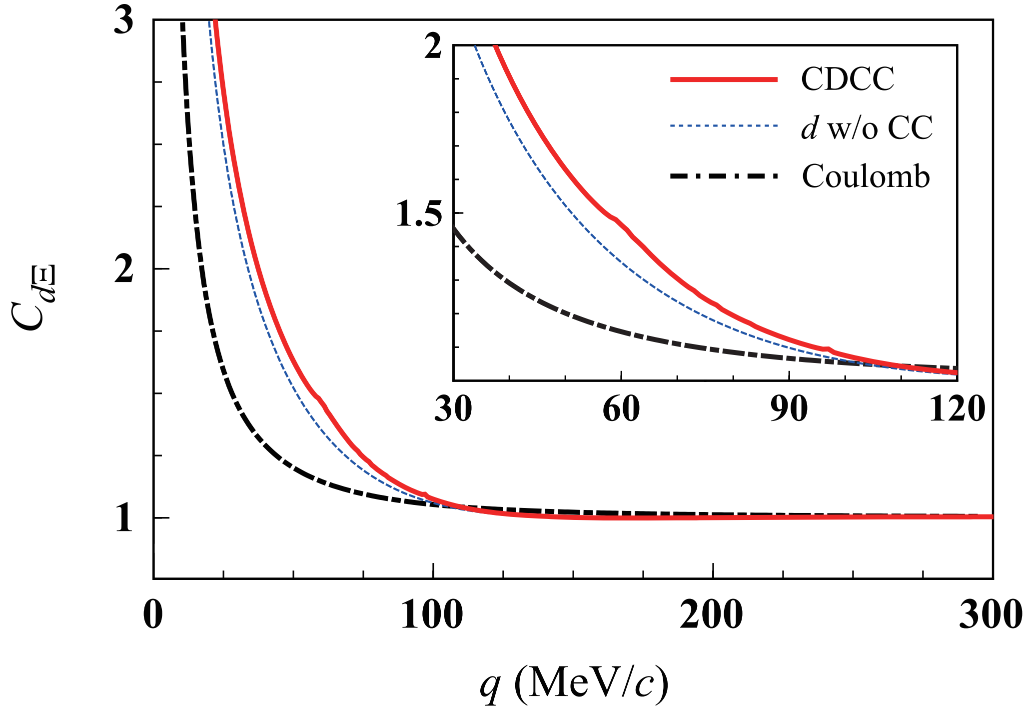

Fig. 2. – Deuteron-Ξ correlation function as a function of q. The red-solid line corresponds to the results obtained with CDCC including the coupled channels effect, while blue-dotted line is the one-channel results by including solely the deuteron channel. The contribution from the pure Coulomb interaction is given by the black-dash-dotted line.

obtained by CDCC, while the black-dash-dotted line corresponds to those computed with the Coulomb interaction only. Because the presence of the strong interaction enhances $C_{d\Xi}$ with respect to the pure Coulomb case, we find that the deuteron-Ξ^- interaction has the attractive nature. Despite the attraction, we obtained the negative value of an s-wave scattering length (within the nuclear-physics convention [31]), indicating that the interaction can form no bound states for the deuteron-Ξ^- system. This weakly attractive nature of the deuteron-Ξ^- interaction in the strangeness $S = -2$ sector is qualitatively consistent with that in the $S = -1$ sector. The deuteron-Λ interaction is attractive but not sufficiently strong to form a bound state, deduced from an analysis of the deuteron-Λ correlation function using the Lednicky-Lyuboshits approach with the effective range expansion [39].

Next, we focus our attention on the coupled-channels effect on $C_{d\Xi}$. The blue-dotted line in fig. 2 is obtained by CDCC but taking into account the deuteron channel only by neglecting all other continuum states. The coupled-channels effect is visible as an increase of $C_{d\Xi}$ by less than 10%. Therefore, we can infer that the direct formation is dominant within the present source function.

In ref. [31], we discussed the mechanism how the coupled-channels effect plays an attractive role by investigating the distorted waves and coupling potentials. Furthermore, the neutron-neutron threshold effect manifesting itself as a small bump of $C_{d\Xi}$ around $q \sim 60$ MeV/c is argued in detail [31].

4. – Conclusion and perspectives

We have calculated the deuteron-Ξ^- correlation function by means of CDCC, a precise and cost-effective three-body model, with which we can take into account the channel coupling among deuteron-Ξ^-, continuum proton-neutron-Ξ^-, and neutron-neutron-Ξ^0 channels. We have found that the deuteron-Ξ^- has attractive nature but not strong enough to form a bound state, the coupled-channels effect is less than 10% on the correlation function, and the direct deuteron production is dominant in heavy-ion collision considered here. As a future study, we plan to improve our calculations by including a three-baryon force and nucleon-Λ-Λ channel, for instance.

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