ΣN and ΛN interactions from $2+1$ flavor lattice QCD with almost physical masses

H. Nemura,[*1,*2] S. Aoki,[*2,*3,*4] T. Doi,[*2,*5] S. Gongyo,[*2] T. Hatsuda,[*2,*5] Y. Ikeda,[*1,*2] T. Inoue,[*2,*6] T. Iritani,[*2] N. Ishii,[*1,*2] T. Miyamoto,[*2,*3] and K. Sasaki[*2,*3]

Nuclear force and strangeness nuclear forces provide an important starting point to understand how hypernuclei are bound, in which hyperons (or strange quarks) are embedded in normal nuclei as "impurities." Determining how such a baryon-baryon (BB) interaction is described from a fundamental perspective is a challenging problem in physics. Although a normal nucleus is successfully described by utilizing the high precision nucleon-nucleon (NN) potentials together with a three-nucleon force a quantitatively same-level description of a hypernucleus is still difficult because of the large uncertainties of hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions; those YN and YY potentials are not well constrained from experimental data owing to the short life time of hyperons. A recent experimental study shows a tendency to repulsive Σ-nucleus interaction[1] and only a four-body Σ-hypernucleus (${}^4_\Sigma$He) is observed; these results suggest a repulsive nature of the ΣN interaction. Such quantitative understanding is useful to study the properties of hyperonic matter inside neutron stars, where the recent observations of a massive neutron star heavier than $2M_\odot$ might raise a problem of the hyperonic equation of state (EOS) employed in such a study. Furthermore, better understanding of YN and YY is becoming increasingly important owing to the observation of the binary neutron star merger.

During the last decade a new lattice QCD approach to study a hadron-hadron interaction was proposed. In this approach, the interhadron potential is obtained by means of the lattice QCD measurement of the Nambu-Bethe-Salpeter (NBS) wave function. The observables such as the phase shifts and the binding energies are calculated by using the resultant potential. A large scale lattice QCD calculation is now in progress[2] to study the baryon interactions from NN to $\Xi\Xi$ by measuring the NBS wave functions for 52 channels[3] from the $2+1$ flavor lattice QCD by employing the almost physical quark masses corresponding to $(m_\pi, m_K) \approx (146, 525)$ MeV and large volume $(La)^4 = (96a)^4 \approx (8.1\ \mathrm{fm})^4$ with the lattice spacing $a \approx 0.085$ fm.

Figure 1 shows the scattering phase shifts of ΣN system with isospin $I = 3/2$ obtained from the nearly physical point lattice QCD calculation through parametrized analytical functions.[2] The top left panel in the figure shows the scattering phase shift in the ${}^1S_0$ channel; the present result shows that the interaction in the ${}^1S_0$ channel is attractive on average. The other three panels in Fig. 1 show the bar-phase shifts and mixing angle in the ${}^3S_1-{}^3D_1$ states, $\bar\delta_0$ (upper right), $\bar\delta_2$ (lower left), and $\bar\varepsilon_1$ (lower right); the phase shift $\bar\delta_0$ shows the interaction is repulsive while the phase shift $\bar\delta_2$ behaves around almost zero degree. The present results are qualitatively consistent with group theoretical classification based on a quark model which is useful for clarifying the general behavior of various BB interactions in the S-wave; the ΣN $I = 3/2$ ${}^3S_1-{}^3D_1$ belongs to **10** which is almost Pauli forbidden while the ΣN $I = 3/2$ ${}^1S_0$ belongs to **27**, which is the same as NN ${}^1S_0$. The present S-wave (dominated) phase shifts, the repulsive (attractive) behavior of $\bar\delta_0$ ($\delta({}^1S_0)$), augur well for future quantitative conclusions with larger statistics. Further calculations to obtain physical quantities with increased statistics are in progress and will be reported elsewhere.

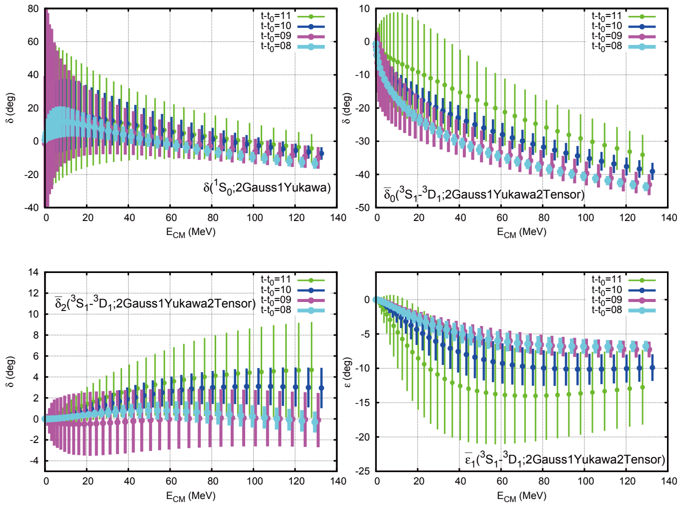

Fig. 1. Scattering (bar-)phase shifts and mixing angle of the $I = 3/2$ ΣN system, $\delta({}^1S_0)$ in the ${}^1S_0$ state (upper left), and $\bar\delta_0$ (upper right), $\bar\delta_2$ (lower left), and $\bar\varepsilon_1$ (lower right) in the ${}^3S_1-{}^3D_1$ states, obtained from the nearly physical point lattice QCD calculation on a volume $(96a)^4 \approx (8.1\ \mathrm{fm})^4$ with the lattice spacing $a \approx 0.085$ fm and $(m_\pi, m_K) \approx (146, 525)$ MeV through parametrized analytical functions.[2]

References

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*1 Research Center for Nuclear Physics, Osaka University
*2 RIKEN Nishina Center
*3 Yukawa Institute for Theoretical Physics, Kyoto University
*4 Center for Computational Sciences, University of Tsukuba
*5 iTHEMS Program and iTHES Research Group, RIKEN
*6 Nihon University, College of Bioresource Sciences