Lattice QCD determination of nuclear and hyperon forces

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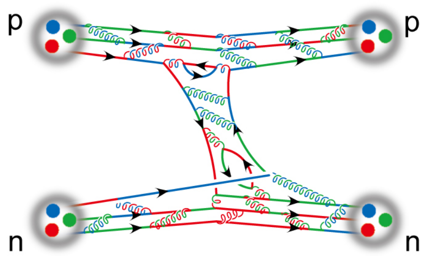

The aim of nuclear physics is to understand various properties of atomic nuclei based on the nucleonic degrees of freedom, where the nuclear force serves as the fundamental interaction. Enormous effort has been devoted to studies of the nuclear force, after the meson-exchange mechanism was proposed by H. Yukawa [1]. Today, thousands of experimental NN scattering data are available. They are used for a phenomenological determination of the nuclear force. Now, there are several high precision realistic nuclear forces available [2], all of which are able to describe the experimental NN scattering data in many channels simultaneously with $\chi^2/\mathrm{ndf} \sim 1$.

In the meson-exchange picture, the nuclear force is generated by virtual exchanges of massive mesons. The mechanism employed here is a generalization the Coulomb force in quantum electrodynamics which is generated by the virtual exchange of massless photon. The structure of the nuclear force is much more complicated than the Coulomb force. This is because varieties of mesons are involved from a wide range of mass spectrum with different spin and isospin quantum numbers [3].

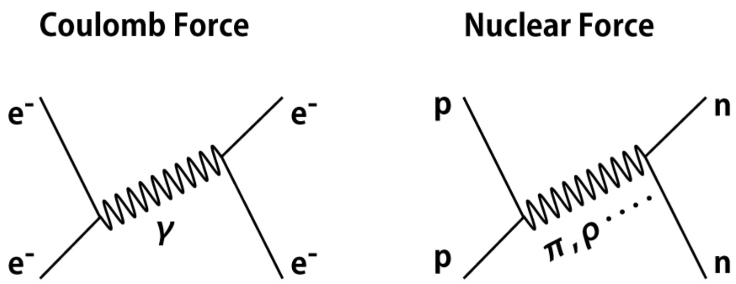

Figure 1: The Coulomb force and the nuclear force.

For many years, the nuclear force has been studied based on varieties of phenomenological approaches such as the meson-exchange and the constituent quark model. Although they provide physics insights into the nature of the nuclear force in their own way, one may wonder if they could involve unknown systematic uncertainties. This is especially the case at short distance where the repulsive core appears which is intimately related to the intrinsic structure of nucleon as multi-quark system. Recently, we propose a method to determine the nuclear force based on the Nambu-Bethe-Salpeter (NBS) wave functions, which makes it possible to study the nuclear force by a direct use of Quantum Chromo Dynamics (QCD) [4].

QCD is the ultimate theory of the strong interaction. It describes the dynamics of quarks and gluons, to which the dynamics of all the hadrons is subject. Due to the asymptotic freedom, the perturbation theory works at high energy. In contract, at low energy, the effective coupling of QCD grows up, and the perturbation expansion breaks down, which gives rise to number of interesting non-perturbative phenomena such as the color confinement and the spontaneous breaking of chiral symmetry.

Lattice QCD Monte Carlo calculation provides an unique tool to study non-perturbative phenomena of QCD. It has successfully reproduced the ground state spectrum of baryons (qqq) and mesons ($q\bar{q}$) [5]. It plays a key role in the high temperature QCD. It is one of the most promising methods to obtain the hadronic matrix elements to go beyond the standard model. Needless to say, lattice QCD can be used to study various properties of atomic nuclei (q^{3A}). At the moment, most of the studies of atomic nuclei are performed in conventional way based on the effective degree's of freedom, i.e., the nucleon. Direct application of QCD to atomic nuclei is just started,

$$\mathcal{L} = \frac{1}{2g^2}\mathrm{Tr}\left(G_{\mu\nu}G^{\mu\nu}\right) + \sum_q \bar{q}\left(i\not{D} - m_q\right)q$$

Figure 2: Quantum Chromo Dynamics (QCD).

which is promoted by the recent improvement of performance of super computers and progress of lattice QCD algorithm which includes our algorithm for the nuclear force [4, 6].

The NBS wave functions is a QCD matrix element which is calculable by the lattice QCD Monte Carlo calculations. It has a remarkable feature that its behavior at large spatial separation is parameterized by the scattering phase in exactly the same manner as scattering wave functions in quantum mechanics of NN theory. If we use the NBS wave functions as inputs, and solve the Schrödinger equation inversely for the potential, we will obtain the nuclear force which is faithful to the scattering phase encoded in the long distance part of the NBS wave functions. This method is known as "HAL QCD method" [4].

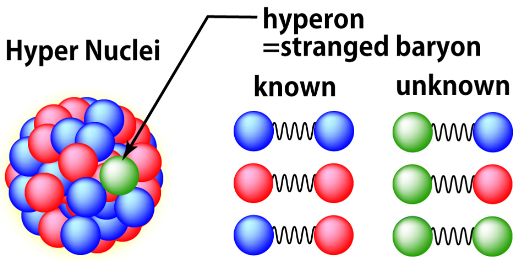

Figure 3: Hyper nuclei and hyperon interactions.

Hyperons are those baryons which contain strange quarks, such as Λ, Σ, Ξ and Ω. Hyper nuclei are those nuclei which contain hyperons. Since hyperons have short lifetime, number of available scattering data is limited, so that the straightforward application of the same method for the nuclear force does not work for a phenomenological determination of the hyperon force. Indeed, the determination of hyperon forces is one of the most important themes at J-PARC in the nuclear physics.

The hyperon force is one of the best targets of HAL QCD method. In fact, the hyperon force is easier to be determined than the nuclear force. This is because the lattice QCD Monte Carlo calculation becomes stable if we include strange quarks which reduces the statistical noises [7].

Flavor SU(3) limit is quite useful in understanding a general trend of hyperon force [8]. It is an idealized limit where up, down and strange quarks have the same mass. As a result, N, Λ, Σ and Ξ become degenerate. They form an eight dimensional irreducible representation (irrep.**8**) of flavor SU(3), which is referred to as the baryon octet. Systems consisting of two octet-baryons are decomposed into six irrep's of flavor SU(3) as $\mathbf{8} \otimes \mathbf{8} = \mathbf{1} \oplus \mathbf{8}_A \oplus \mathbf{8}_S \oplus \mathbf{10} \oplus \mathbf{10}^* \oplus \mathbf{27}$. The flavor dependence of the potential is found to be large. These six irrep's lead to six different hyperon potentials. Among others, the irrep.**1** is the most interesting. It does not have the repulsive core at short distance, and is attractive in all spatial region. A six quark state ($uuddss$) is found to exist as a bound state in the irrep.**1** [9]. It is known as "H-dibaryon", a typical exotic hadron which attracts a longstanding interest from strangeness nuclear physics.

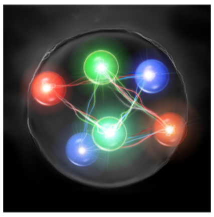

Figure 4: Artist's impression of H dibaryon as a six quark state.

Flavor SU(3) symmetry is broken in the real world. The degeneracy of the octet baryons splits into N, Λ, Σ and Ξ. It is now necessary to consider the quark rearrangement processes explicitly such as $\Lambda(uds)\Lambda(uds) \to N(uud)\Xi(dss)$, which amounts to a coupled channel scattering problem.

Lüscher's finite volume method is the standard tool for the scattering

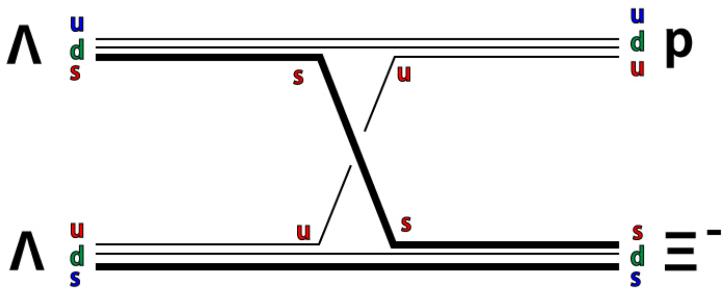

Figure 5: Coupled channel scattering $\Lambda(uds)\Lambda(uds) \to N(udu)\Xi^-(sds)$.

problem in lattice QCD. It however is restricted to elastic scatterings. Extension of Lüscher's method to coupled channel scatterings is not straightforward. This is because asymptotic scattering states are not separately obtained in the finite volume. In contrast, extension of HAL QCD method to coupled channel scatterings is straightforward, because a potential is confined in the spatially compact region. It enables us to unveil the nature of the H-dibaryon in the flavor SU(3) broken world [11].

For many years, applications of HAL QCD method was restricted to the central and tensor potentials in even parity sector. This is because these potentials are calculated from S-wave and D-wave components of NBS wave functions, which are easily obtained by lattice QCD. Recently, based on the representation theory of the cubic group, we developed a systematic method to generate NBS wave functions in various partial waves. As a result, it is now possible to calculate the nuclear force in parity odd sectors and spin-orbit (LS) force by HAL QCD method [12].

LS force plays an important role in the nuclear physics. It gives an important influence on the magic number of atomic nuclei. It is pointed out that LS force induces P-wave super conductivity at high density in neutron star. Application of the cubic group technique leads to not only the conventional LS force but also the anti-symmetric LS force, which is a new term appearing in the generalization of the nuclear force to hyperon sectors. The anti-symmetric LS force is expected to play a key role in understanding the spin-orbit puzzle in the Λ hyper nuclei.

Until quite recent, lattice QCD calculations had been restricted to those calculations which employ an artificially heavy quark mass. These calculations have to involve a necessary extrapolation to the physical quark mass, which can be a source of systematic uncertainties. Recently, progress of lattice QCD Monte Carlo algorithm and significant improvement of performance of super computers made it possible to perform lattice QCD calculation directly employing the physical quark mass. To study the nuclear force by directly employing the physical quark mass, a huge spatial volume is required to accommodate two-nucleon system. By using K computer, HPCI (High Performance Computation Infrastructure) strategic program field 5 has generated gauge field configuration at almost physical pion mass $m_\pi \simeq 145$ MeV on a large spatial volume $L \simeq 8$ fm. These gauge configurations are currently used to study the physics of nuclei and hyper nuclei directly based on the lattice QCD first principle calculations [13].

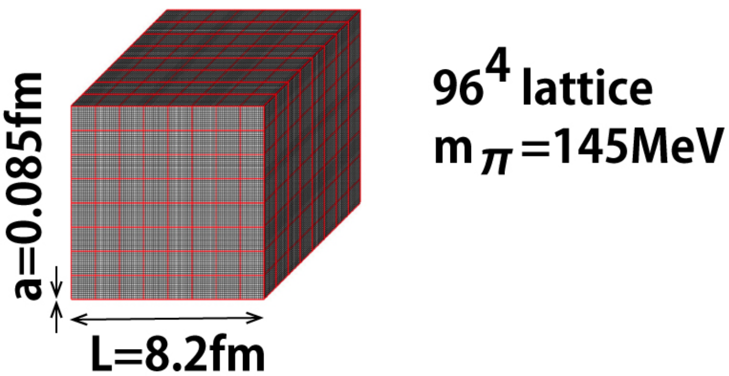

Figure 6: Artist's impression of the physical point gauge configuration generated by K computer at RIKEN AICS.

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