Structure of light hypernuclei and YN, YY interaction

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1 Introduction

One of the main goals in hypernuclear physics is to understand the baryon-baryon interaction in a unified model and to study the structure of multi-strangeness systems. The baryon-baryon interaction is fundamental and important for the study of nuclear physics. In order to understand the baryon-baryon interaction, two-body scattering experiment is the most useful. For this purpose, many NN scattering experiments have been done so far and total number of NN data are about 4,000. However, due to the difficulty of performing two-body hyperon(Y)-nucleon(N) and hyperon(Y)-hyperon(Y) scattering experiments, the total number of YN scattering data are very limited. Namely, the number of differebtial cross section are only about 40 and there is no YY scattering data. Therefore, YN and YY potential models so far proposed have large ambiguity.

Therefore, as a substitute for the two-body limited YN and non-exixtant YY scattering data, the systematic investigation of light hyperuclear structure is essential.

Especially, it is interesting to investigate the structure of the multi-strangeness system when one or more Λs are added to a nucleus. It is conjectured that extreme limit, which includes many Λs in nuclear matter is the core of a neutron star. In this meaning, the sector of $S = -2$ nuclei, double Λ hypernuclei and Ξ hypernuclei is just the entrance to the multi-strangeness world. However, we have hardly any knowledge of the YY interaction because there exist no YY scattering data. Then, in order to understand the YY interaction, it is crucial to study the structure of double Λ hypernuclei and Ξ hypernuclei.

2 Structure of double Λ hypernuclei

Recently, the epock-making data has been reprote by the KEK-E373 experiment. Namely, the double Λ hypernucleus, ${}^{6}_{\Lambda\Lambda}$He was observed [1]. This observation was called NAGARA event. The formation of ${}^{6}_{\Lambda\Lambda}$He was uniquely identified by the observation of sequential weak decays, and the precise experimental value of the 2Λ binding (separation) energy, $B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}$ MeV, was obtained. Following the strategy mentioned in Section ??, (1) we employed Nijmegen model D $\Lambda\Lambda$ interaction. (2)And we performed $\alpha\Lambda\Lambda$ three-body calculation. (3)By comparing between the theoretical result with the experimental data of the binding energy of ${}^{6}_{\Lambda\Lambda}$He, it was suggested to reduce the strength of ${}^{1}S_0$ term of the $\Lambda\Lambda$ potential by half. (4)Then, usig the improved potential, it is interesting to predict spectra of new double Λ hypernuclei. In fact, at J-PARC, it is planned to produce many double Λ hypernuclei by emulsion expreiment [2]. However, it is difficult to determine spin-parities and whether the observed state is the ground state or an excited state. Therefore, it is necessary to compare the data with theoretical calculation for the identification of the state. The author's role is to contribute to theoretical calculation using few-body calculational method.

A successful example to determine spin-parity of double Λ hypernuclei is 'Demachi-Yanagi' event for ${}^{10}_{\Lambda\Lambda}$Be. There is one more event found in the E373 experiment named the 'Demachi-

Yanagi' event [3, 4] The most probble interpretation of this event is the production of a bound state of ${}^{10}_{\Lambda\Lambda}$Be haveing $B^{\rm exp}_{\Lambda\Lambda} = 12.33^{+0.35}_{-0.21}$ MeV. But experiment could not determine whether this state was observation of the ground state or any excited state. In order to determine this, our calculation [5] mentioned above was useful as following: We studied ${}^{10}_{\Lambda\Lambda}$Be by employing an $\alpha+\alpha+\Lambda+\Lambda$ four-body model. The calculated value of $B_{\Lambda\Lambda}({}^{10}_{\Lambda\Lambda}{\rm Be}(2^+))$ is 12.28 MeV that agrees with the experimental data. Therefore, the Demachi-Yanagi event can be interpreted most probably as the observation of the 2^+ excited state in ${}^{10}_{\Lambda\Lambda}$Be.

In this way, we succeeded in interpreting the spin-parity of ${}^{10}_{\Lambda\Lambda}$Be by comparing the experimental data and our theoretical calculation.

In the KEK-E373 experiments, they have observed the two events of double Λ hypernuclei, named as Nagara, Demachi-Yanagi [1, 6]. Recently, since the mass of Ξ^- has been modified by 0.4 MeV in the PDB, they have re-analyzed them to be $B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV for ${}^{6}_{\Lambda\Lambda}$He and to be $B_{\Lambda\Lambda} = 11.90 \pm 0.13$ MeV for ${}^{10}_{\Lambda\Lambda}$Be. Also, in the KEK-E373 experiments, they observed one more event, Hida event [6]. This observation is for ${}^{11}_{\Lambda\Lambda}$Be or ${}^{12}_{\Lambda\Lambda}$Be. The observed $B_{\Lambda\Lambda}$ for ${}^{11}_{\Lambda\Lambda}$Be is 20.49 ± 1.15 MeV and $B_{\Lambda\Lambda}$ for ${}^{12}_{\Lambda\Lambda}$Be is 22.06 ± 1.15 MeV [6]. The important issue is to interpret the Hida event as a ground state or excited state in ${}^{11}_{\Lambda\Lambda}$Be or ${}^{12}_{\Lambda\Lambda}$Be. We assume Hida event as ${}^{11}_{\Lambda\Lambda}$Be and calculate the $B_{\Lambda\Lambda}$ with $\alpha\alpha n\Lambda\Lambda$ five-body problem. This five-body calculation is numerically difficult since we have three kinds of particles such as α, Λ and neutron, and we have five different kinds of interactions such as $\Lambda\Lambda$, Λn, $\Lambda\alpha$, $n\alpha$ and $\alpha\alpha$, and we have Pauli principle between α and α, and between α and neutron. Recently, we succeeded in performing this calculation.

In the present $\alpha+\alpha+n+\Lambda+\Lambda$ five-body model for ${}^{11}_{\Lambda\Lambda}$Be, it is absolutely necessary that all sub-cluster systems composed of two α's, a neutron and two Λ's are described reasonably with the interactions among these units. In our previous work [5], our interactions, which include the $\alpha\alpha$, αn, $\alpha\Lambda$, Λn and $\Lambda\Lambda$ interactions, were determined so as to reproduce reasonably well the following observed quantities: (i) Energies of the low-lying states and scattering phase shifts in the $\alpha+n$ and $\alpha+\alpha$ systems, (ii) Λ-binding energies B_Λ in ${}^{5}_{\Lambda}$He $(=\alpha+\Lambda)$, ${}^{6}_{\Lambda}$He $(=\alpha+\Lambda+n)$ and ${}^{9}_{\Lambda}$Be $(=\alpha+\alpha+\Lambda)$, (iii) double-Λ binding energies $B_{\Lambda\Lambda}$ in ${}^{6}_{\Lambda\Lambda}$He $(=\alpha+\Lambda+\Lambda)$, the Nagara event. Then, as mentioned above, the Demachi-Yanagi event for ${}^{10}_{\Lambda\Lambda}$Be $(=\alpha+\alpha+\Lambda+\Lambda)$ was simultaneously reproduced with no additional adjustable parameter.

In the present work, we employ the same interactions of Ref.[5] so that those severe constraints are also successfully met in our two-, three- and four-body subsystems. But, as for the present core nucleus ^{9}Be $(=\alpha+\alpha+n)$, which does not belong to the subsystems studied previously, use of the interactions that explain well the property of the $\alpha\alpha$ and αn subsystems do not well reproduce the energies of the low-lying states of ^{9}Be measured from the $\alpha+\alpha+n$ threshold (the same property of the calculated result was reported in another microscopic $\alpha+\alpha+n$ cluster-model study [7]). Therefore, we additionally introduce a phenomenological $\alpha\alpha n$ three-body force with a Gaussian shape, $v_0 e^{-(r_{\alpha-\alpha}/r_0)^2-(R_{\alpha\alpha-n}/R_0)^2}$, having $r_0 = 3.6$ fm, $R_0 = 2.0$ fm and $v_0 = -9.7$ MeV $(+13.0$ MeV$)$ for the negative-parity (positive-parity) state; we thus reproduce well the observed energies of the $3/2^-_1, 5/2^-_1, 1/2^-_1$ and $1/2^+_1$ states of ^{9}Be. The calculated value of $B_{\Lambda\Lambda}({}^{11}_{\Lambda\Lambda}{\rm Be})$ is 18.23 MeV for the $3/2^-$ ground state, while for the excited states the $B_{\Lambda\Lambda}$ values are calculated to be less than 15.5 MeV. Therefore, the observed Hida event can be interpreted to be the ground state. When our calculated binding energy is compared with the experimental value of 20.83 MeV with a large uncertainty of σ=1.27 MeV, we can say at least that our result does not contradict the data within 2σ. Motivated by the recent observation of the Hida event for a new double Λ hypernucleus, we have succeeded in performing a five-body calculation of ${}^{11}_{\Lambda\Lambda}$Be using an $\alpha\alpha n\Lambda\Lambda$ cluster model. The calculated $\Lambda\Lambda$ binding energy does not contradict the interpretation that the Hida event is an observation of the ground state of ${}^{11}_{\Lambda\Lambda}$Be.

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