A new three-baryon-force in ΛΛ hypernuclei

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A new three-baryon-force in $\Lambda\Lambda$ hypernuclei

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Abstract. We describe a few-body calculation of $^{5}_{\Lambda\Lambda}$H as well as $^{4}_{\Lambda\Lambda}$H and $^{6}_{\Lambda\Lambda}$He taking account fully coupled-channel two-baryon potentials acting among the octet of baryons. The wave function includes not only $pnn\Lambda\Lambda$ and $ppnn\Xi^-$ components but also $pnn\Lambda\Sigma^0$, $ppn\Lambda\Sigma^-$, $pnn\Sigma^0\Sigma^0$ and $ppn\Sigma^0\Sigma^-$. An effective YY potential based on Nijmegen model D is used. We find that the $pnn\Lambda\Sigma^0$ and $ppn\Lambda\Sigma^-$ components play an important role in producing the $^{5}_{\Lambda\Lambda}$H bound state. The present result requires the introduction of a new coupled-channel three-body-force, $N\Lambda\Lambda - NN\Xi$, if the intermediate $pnn\Lambda\Sigma^0$ and $ppn\Lambda\Sigma^-$ states are eliminated from the model space.

Keywords: three-body-force, few-body problem, strangeness, hypernuclei
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INTRODUCTION

Doubly-strange, light hypernuclear systems are important to study in order to understand the baryon-baryon interactions, including the hyperon-hyperon (YY) potential as well as the hyperon-nucleon (YN) potential. In the study of strangeness $S = -1$ s-shell hypernuclei, it has been demonstrated that the $\Lambda N - \Sigma N$ coupled-channel potential plays a significant role in explaining the anomalously small binding of $^{5}_{\Lambda}$He[1]. The "coherent $\Lambda - \Sigma$ coupling"[1] may also be important in doubly strange hypernuclei.

A $\Lambda\Lambda$ two-body system couples to the $N\Xi$ and $\Sigma\Sigma$ states in free space. For the doubly strange ($S = -2$) hypernucleus, $^{5}_{\Lambda\Lambda}$H, the *core nucleus* + $\Lambda\Lambda$ system couples to the *core nucleus* + $\Lambda\Sigma$ component. This is an extension of the coherent $\Lambda - \Sigma$ coupling to the doubly strange hypernucleus, and it implies that $\Lambda N - \Sigma N$ coupling should also play an important role in the binding mechanism of the doubly strange hypernuclei. Therefore, precise calculations of the light $\Lambda\Lambda$ hypernuclei should be made in a fully coupled channel formulation taking account of explicit Σ degrees of freedom. The purpose of this study is to describe a few-body calculation of the s-shell hypernuclei with $S = -2$ by taking account of the explicit Σ degrees of freedom in a framework of a fully coupled-channel formulation.

INTERACTIONS AND METHOD

We assume that the wave function of a system with $S = -2$, comprising $A(= 4 - 6)$ octet baryons, has four isospin-basis components. For example, the $^{5}_{\Lambda\Lambda}$H has four isospin components as $pnn\Lambda\Lambda$, $NNNNN\Xi$, $NNNN\Lambda\Sigma$ and $NNNN\Sigma\Sigma$. We abbreviate these components as $\Lambda\Lambda$, $N\Xi$, $\Lambda\Sigma$ and $\Sigma\Sigma$, referring to the last two baryons. The Hamiltonian

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of the system is hence given by 4×4 components as

$$H = \begin{pmatrix} H_{\Lambda\Lambda} & V_{N\Xi-\Lambda\Lambda} & V_{\Lambda\Sigma-\Lambda\Lambda} & V_{\Sigma\Sigma-\Lambda\Lambda} \\ V_{\Lambda\Lambda-N\Xi} & H_{N\Xi} & V_{\Lambda\Sigma-N\Xi} & V_{\Sigma\Sigma-N\Xi} \\ V_{\Lambda\Lambda-\Lambda\Sigma} & V_{N\Xi-\Lambda\Sigma} & H_{\Lambda\Sigma} & V_{\Sigma\Sigma-\Lambda\Sigma} \\ V_{\Lambda\Lambda-\Sigma\Sigma} & V_{N\Xi-\Sigma\Sigma} & V_{\Lambda\Sigma-\Sigma\Sigma} & H_{\Sigma\Sigma} \end{pmatrix}, \tag{1}$$

where $H_{B_1B_2}$ operates on the B_1B_2 component,

$$\begin{aligned} H_{B_1B_2} &= \sum_{i=1}^{A}\left(\frac{\mathbf{p}_i^2}{2m_i}+m_ic^2\right) - T_{c.m.} + \sum_{i<j}^{A-2} v_{NN}(\mathbf{r}_i-\mathbf{r}_j) + \sum_{j=1}^{2}\sum_{i=1}^{A-2} v_{NB_j}(\mathbf{r}_i-\mathbf{r}_{B_j}) \\ &\quad + v_{B_1B_2}(\mathbf{r}_{B_1}-\mathbf{r}_{B_2}) + \sum_{i<j}^{A}\frac{q_iq_j}{|\mathbf{r}_i-\mathbf{r}_j|}, \end{aligned} \tag{2}$$

and $V_{B_1B_2-B_1'B_2'}$ is the sum of all possible two-body transition potentials connecting the B_1B_2 and $B_1'B_2'$ components:

$$V_{\Lambda\Lambda-N\Xi} = v_{\Lambda\Lambda-N\Xi}, \quad V_{\Lambda\Lambda-\Lambda\Sigma} = \sum_{i=1}^{N} v_{N_i\Lambda-N_i\Sigma}, \quad V_{N\Xi-\Lambda\Sigma} = v_{N\Xi-\Lambda\Sigma}, \tag{3}$$

$$V_{\Lambda\Lambda-\Sigma\Sigma} = v_{\Lambda\Lambda-\Sigma\Sigma}, \quad V_{N\Xi-\Sigma\Sigma} = v_{N\Xi-\Sigma\Sigma}, \quad V_{\Lambda\Sigma-\Sigma\Sigma} = \sum_{i=1}^{N} v_{N_i\Lambda-N_i\Sigma} + v_{\Lambda\Sigma-\Sigma\Sigma}. \tag{4}$$

In the present calculations, we use the Minnesota potential[2] for the NN interaction and the D2′ potential for the YN interaction. The Minnesota potential reproduces reasonably well both the binding energies and sizes of few-nucleon systems. The D2′ potential is a modified potential based upon the original D2 potential[1]. The strength of the long-range part (V_b in Table I of Ref. [1]) of the D2′ potential in the ΛN-ΛN $^3S_1$ channel is reduced by multiplying by a factor (0.954) in order to reproduce the experimental $B_\Lambda(^5_\Lambda\mathrm{He})$ value.

For the YY interaction, we use a full-coupled channel potential among the octet baryons in both the spin triplet and the spin singlet channels. We assume that the YY potential consists of only the central component, and the effect due to the non-central force (e.g., tensor force) should be effectively included in the central part. The parameters are selected to reproduce the low-energy S matrix of the Nijmegen hard-core model D (ND)[3]. We take the hard-core radius to be $r_c = 0.56(0.45)$ fm in the spin singlet (triplet) channel. Each number is the same as the hard-core radius of the YN sector in each channel. We denote as ND_S the potential simulating the ND model.

The binding energy is calculated in a complete A-body treatment. Since all of the exotic components ($\Lambda\Lambda$, $N\Xi$, $\Lambda\Sigma$ and $\Sigma\Sigma$) are taken into account, the variational trial function must be flexible enough to accurately search the eigenenergies. The trial function is given by a combination of basis functions:

$$\Psi = \sum_{k=1}^{K} c_k\varphi_k, \qquad \text{with} \qquad \varphi_k = \mathscr{A}\{G(\mathbf{x};A_k)\chi_{kJM}\eta_{kIM_I}\}. \tag{5}$$

Here $\mathscr{A}$ is an antisymmetrizer acting on the identical particles. For the spin χ_k and the isospin η_k functions, all possible configurations are taken into account. The abbreviation $\mathbf{x} = (\mathbf{x}_1, \cdots, \mathbf{x}_{A-1})$ is a set of relative coordinates. For the spatial part, the basis function is constructed by the correlated Gaussian (CG), $G(\mathbf{x}; A_k)$, which is given by

$$G(\mathbf{x}; A_k) = \exp\left\{-\frac{1}{2}\sum_{i<j}^{A} \alpha_{kij}(\mathbf{r}_i - \mathbf{r}_j)^2\right\} = \exp\left\{-\frac{1}{2}\sum_{i,j=1}^{A-1} A_{kij}\mathbf{x}_i \cdot \mathbf{x}_j\right\}. \qquad (6)$$

The stochastic variational method[4, 5] with the above CG basis produces accurate solutions. The reader is referred to Refs.[5, 6, 7] for details.

RESULTS

Table 1 lists the $B_{\Lambda\Lambda}$ values for the $S = -2$ hypernuclei. We have obtained the bound-state solutions for ${}^{4}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$H and ${}^{6}_{\Lambda\Lambda}$He. For ${}^{6}_{\Lambda\Lambda}$He, the $\Lambda\Lambda$ interaction energy ($\Delta B_{\Lambda\Lambda}$) is given by

$$\Delta B^{(\mathrm{calc})}_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = B^{(\mathrm{calc})}_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B^{(\mathrm{calc})}_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) = 1.59\mathrm{MeV}, \qquad (7)$$

which is slightly larger than the experimental value,[8]

$$\Delta B^{(\mathrm{exp})}_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 1.01 \pm 0.20^{+0.18}_{-0.11}\mathrm{MeV}.$$

We have also calculated these systems using a modified ND$_S$ (mND$_S$) YY potential; The strength of the $\Lambda\Lambda$ diagonal part of the mND$_S$ potential is reduced by multiplying the original ND$_S$ by a factor of 0.8 in order to reproduce the experimental $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$. Hereafter we use the mND$_S$ potential rather than the ND$_S$. Table 2 shows the probabilities for the $N\Xi$, $\Lambda\Sigma$ and $\Sigma\Sigma$ components of the $S = -2$ hypernuclei. We should emphasize that the probability of the $N\Xi$ component, $P_{N\Xi}({}^{5}_{\Lambda\Lambda}\mathrm{H})$, has a surprisingly large value (4.56%) in spite of the fact that the $\Lambda\Lambda - N\Xi$ coupling of the ND is rather weak as will be seen later. This is in remarkable contrast with other calculations based on $(t + \Lambda + \Lambda)$ and $(\alpha + \Xi^-)$ two-channel model[9, 10]. We obtained a sizable value for the $P_{\Lambda\Sigma}({}^{5}_{\Lambda\Lambda}\mathrm{H})$ probability. The $\Lambda\Sigma$ component couples to the $\Lambda\Lambda$ component via the $v_{N\Lambda-N\Sigma}$ potential, as can be seen in Eq. (3), whereas the $v_{\Lambda\Lambda-N\Xi-\Sigma\Sigma}$ potential in the ${}^{1}S_0$, $I = 0$ channel does not directly connect the $\Lambda\Sigma$ component and the $\Lambda\Lambda$ component. $P_{\Sigma\Sigma}$'s are

TABLE 1. $\Lambda\Lambda$ separation energies, given in units of MeV, for the $A = 4-6$, $S = -2$ s-shell hypernuclei.

YY	$B_{\Lambda\Lambda}({}^{4}_{\Lambda\Lambda}\mathrm{H})$	$B_{\Lambda\Lambda}({}^{5}_{\Lambda\Lambda}\mathrm{H})$	$B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$
ND$_S$	0.107	4.05	7.94
mND$_S$	0.058	3.75	7.54
Exp			$7.25 \pm 0.19^{+0.18}_{-0.11}$

TABLE 2. Probabilities, given in percent, for the $N\Xi$, $\Lambda\Sigma$ and $\Sigma\Sigma$ components of the $A = 4-6$, $S = -2$ s-shell hypernuclei.

	${}^{4}_{\Lambda\Lambda}\mathrm{H}$			${}^{5}_{\Lambda\Lambda}\mathrm{H}$			${}^{6}_{\Lambda\Lambda}\mathrm{He}$		
	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$
mND$_S$	0.06	0.25	0.00	4.56	2.49	0.06	0.28	1.17	0.05

very small for both systems, due to a large mass difference between the $\Lambda\Lambda$ and $\Sigma\Sigma$ channels ($m_{\Sigma\Sigma} - m_{\Lambda\Lambda} \cong 155$ MeV).

Although the present calculation assumes no simplified structures, such as $(t+\Lambda+\Lambda)$ and $(\alpha+\Xi^-)$, this kind of model is useful to provide a clear explanation of the complicated full coupling dynamics of the $A = 5, S = -2$ hypernucleus. Let us consider a set of simple *core nucleus* $+\, Y(+Y)$ model wave functions for the ${}^{5}_{\Lambda\Lambda}\mathrm{H}$:

$$|{}^{5}_{\Lambda\Lambda}\mathrm{H}\rangle = \psi_t \times \psi_{\Lambda\Lambda} \times \psi_{\Lambda\Lambda-t}, \qquad |{}^{5}_{\Xi}\mathrm{H}\rangle = \psi_\alpha \times \psi_{\Xi^-} \times \psi_{\Xi^- -\alpha}, \tag{8}$$

$$|{}^{5}_{\Lambda\Sigma}\mathrm{H}\rangle_{S_{\Lambda\Sigma}} = \sqrt{\frac{1}{3}}\left[\psi_t \times [\psi_{\Lambda\Sigma^0}]_{S_{\Lambda\Sigma}}\right] \times \psi_{\Lambda\Sigma^0-t} - \sqrt{\frac{2}{3}}\left[\psi_h \times [\psi_{\Lambda\Sigma^-}]_{S_{\Lambda\Sigma}}\right] \times \psi_{\Lambda\Sigma^- -h}$$
$$(\text{for } S_{\Lambda\Sigma} = 0 \text{ or } 1), \tag{9}$$

where ψ_c $(c = t, h, \alpha)$ is the wave function (WF) of the core nucleus, ψ_{YY} $(YY = \Lambda\Lambda, \Xi^-, \Lambda\Sigma)$ is the WF of the hyperon(s), and ψ_{YY-c} is the WF that describes the relative motion between YY and c. We assume that all of the baryons occupy the same $(0s)$ orbit. For the ${}^{5}_{\Lambda\Sigma}\mathrm{H}$ state, we have two independent states for the WF $\psi_{\Lambda\Sigma}$, that the spin of two hyperons $(S_{\Lambda\Sigma})$ is either a singlet or a triplet. Since the $\Sigma\Sigma$ component plays a minor role, we omit the ${}^{5}_{\Sigma\Sigma}\mathrm{H}$ state. Using these WFs, we can obtain the algebraic factors for each averaged coupling potential of the allowed spin state, $\bar{v}^s$ or $\bar{v}^t$:

$$\langle V_{\Lambda\Lambda-N\Xi}\rangle = \sqrt{\frac{1}{2}}\bar{v}^s_{\Lambda\Lambda-N\Xi}, \tag{10}$$

$$\langle V_{\Lambda\Lambda-\Lambda\Sigma}\rangle = \begin{cases} \sqrt{\frac{9}{8}}\bar{v}^t_{N\Lambda-N\Sigma} + \sqrt{\frac{1}{8}}\bar{v}^s_{N\Lambda-N\Sigma} & (\text{for } S_{\Lambda\Sigma} = 0), \\ \sqrt{\frac{3}{8}}\bar{v}^t_{N\Lambda-N\Sigma} - \sqrt{\frac{3}{8}}\bar{v}^s_{N\Lambda-N\Sigma} & (\text{for } S_{\Lambda\Sigma} = 1), \end{cases} \tag{11}$$

$$\langle V_{N\Xi-\Lambda\Sigma}\rangle = \begin{cases} -\sqrt{\frac{3}{4}}\bar{v}^s_{N\Xi-\Lambda\Sigma} & (\text{for } S_{\Lambda\Sigma} = 0), \\ \frac{3}{2}\bar{v}^t_{N\Xi-\Lambda\Sigma} & (\text{for } S_{\Lambda\Sigma} = 1). \end{cases} \tag{12}$$

The $v_{\Lambda\Lambda-N\Xi}$ potential is suppressed by a factor of $\sqrt{1/2}$ for the $A = 5$ hypernucleus. The $v_{N\Lambda-N\Sigma}$ and $v_{N\Xi-\Lambda\Sigma}$ potentials, particularly in the spin triplet channel, play significant roles instead. Namely, these equations imply that the $\Lambda\Sigma$ component strongly couples both to the $\Lambda\Lambda$ and to the $N\Xi$ components, and the $\Lambda\Sigma$ component plays a crucial role in the hypernucleus.

The normalized energy expectation values of the Hamiltonian (1) for ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ are (given in units of MeV),

$$h = \begin{pmatrix} \frac{\langle H_{\Lambda\Lambda}\rangle}{P_{\Lambda\Lambda}} & \frac{\langle V_{N\Xi-\Lambda\Lambda}\rangle}{\sqrt{P_{\Lambda\Lambda}P_{N\Xi}}} & \frac{\langle V_{\Lambda\Sigma-\Lambda\Lambda}\rangle}{\sqrt{P_{\Lambda\Lambda}P_{\Lambda\Sigma}}} \\ \frac{\langle V_{\Lambda\Lambda-N\Xi}\rangle}{\sqrt{P_{\Lambda\Lambda}P_{N\Xi}}} & \frac{\langle H_{N\Xi}\rangle}{P_{N\Xi}} & \frac{\langle V_{\Lambda\Sigma-N\Xi}\rangle}{\sqrt{P_{N\Xi}P_{\Lambda\Sigma}}} \\ \frac{\langle V_{\Lambda\Lambda-\Lambda\Sigma}\rangle}{\sqrt{P_{\Lambda\Lambda}P_{\Lambda\Sigma}}} & \frac{\langle V_{N\Xi-\Lambda\Sigma}\rangle}{\sqrt{P_{N\Xi}P_{\Lambda\Sigma}}} & \frac{\langle H_{\Lambda\Sigma}\rangle}{P_{\Lambda\Sigma}} \end{pmatrix} = \begin{pmatrix} -9.12 & -1.82 & -14.52 \\ -1.82 & 5.01 & -10.39 \\ -14.52 & -10.39 & 92.41 \end{pmatrix}. \quad (13)$$

Here, we display only the 3×3 components of the Hamiltonian (1), comprising $\Lambda\Lambda$, $N\Xi$, and $\Lambda\Sigma$, since the contributions from the $\Sigma\Sigma$ component are not large. These numbers reflect the nature of the YY potential model (ND). The ND model has a weak $\Lambda\Lambda$-$N\Xi$ coupling and a weakly attractive $N\Xi$-$N\Xi$ potential.

If we solve the eigenvalue problem, $\det(h-\lambda I)=0$, we obtain the ground state energy, $E=-11.82$ MeV, and the probability, $P_{N\Xi}=3.99\%$. On the other hand, if we ignore the third row and the third column, the eigenenergy of only the first 2×2 subspace becomes $E=-9.35$ MeV, and the probability, $P_{N\Xi}=1.57\%$. This clearly means that the couplings between the ($\Lambda\Lambda$, $N\Xi$) and $\Lambda\Sigma$ components play crucial roles to make ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ bound. The large coupling potentials, $\langle V_{\Lambda\Lambda-\Lambda\Sigma}\rangle$ and $\langle V_{N\Xi-\Lambda\Sigma}\rangle$, also enhance the $P_{N\Xi}$ probability.

COUPLED-CHANNEL THREE-BARYON-FORCE

A coupled-channel Schrödinger equation for three component is written as

$$\begin{pmatrix} h_A & u_{AB} & u_{AC} \\ u_{AB} & h_B & u_{BC} \\ u_{AC} & u_{BC} & h_C \end{pmatrix} \begin{pmatrix} \psi_A \\ \psi_B \\ \psi_C \end{pmatrix} = \varepsilon \begin{pmatrix} \psi_A \\ \psi_B \\ \psi_C \end{pmatrix}. \quad (14)$$

Here the subscript (A,B,C) reads ($\Lambda\Lambda$,$N\Xi$,$\Lambda\Sigma$). The third component yields

$$\psi_C = (\varepsilon - h_C)^{-1} u_{AC}\psi_A + (\varepsilon - h_C)^{-1} u_{BC}\psi_B. \quad (15)$$

Substituting the (15) into (14), we obtain the effective 2×2 Schrödinger equation

$$\begin{pmatrix} \widetilde{h}_A & \widetilde{u}_{AB} \\ \widetilde{u}_{AB} & \widetilde{h}_B \end{pmatrix} \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = \varepsilon \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}, \quad (16)$$

where

$$\widetilde{h}_X = h_X + u_{XC}(\varepsilon - h_C)^{-1} u_{XC}, \qquad (X = A,B) \quad (17)$$

$$\widetilde{u}_{AB} = u_{AB} + u_{AC}(\varepsilon - h_C)^{-1} u_{BC}. \quad (18)$$

Therefore, the effective three-baryon-force is given by

$$w_{AB} = u_{AC}(\varepsilon - h_C)^{-1} u_{BC}. \quad (19)$$

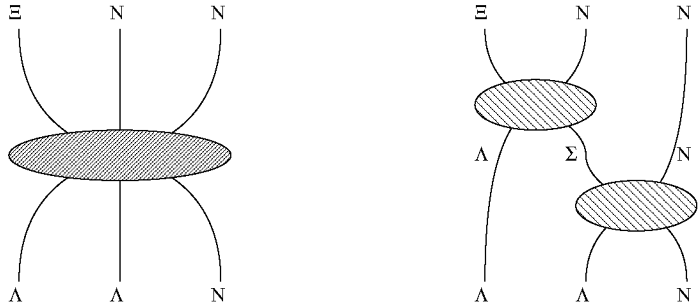

FIGURE 1. Schematic description of coupled-channel three-body-force $\Lambda\Lambda N - \Xi NN$ (left), derived from the intermediate $\Lambda\Sigma$ component (right).

Figure 1 shows a diagram of the $\Lambda\Lambda N - \Xi NN$ three-body-force due to the intermediate $\Lambda\Sigma N$ excitation. In the present case, we can deduce the energy expectation value of the coupled-channel three-baryon-force $\Lambda\Lambda N - \Xi NN$ by eliminating the $\Lambda\Sigma$ component,

$$\langle w_{\Lambda\Lambda - N\Xi} \rangle \cong -1.4 \text{ MeV}. \tag{20}$$

This has almost the same magnitude as the energy expectation value of the original $v_{\Lambda\Lambda - N\Xi}$ potential ($\cong -1.8$ MeV). The net attractive energy due to the $\Lambda\Lambda - N\Xi$ coupling thus becomes approximately three times larger than the original two-body $\Lambda\Lambda - N\Xi$ potential.

The present study is a first attempt to explore the new three-body-force arising in $\Lambda\Lambda$ hypernuclei. This kind of coupled-channel three-baryon-force should be taken into account for the study of Ξ hypernuclei since it affects the net $\Lambda\Lambda - N\Xi$ coupling and the decay width of the hypernucleus.

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REFERENCES

1. Y. Akaishi, et al., Phys. Rev. Lett. **84**, 3539 (2000).
2. D. R. Thompson, M. Lemere and Y. C. Tang, Nucl. Phys. A**286**, 53 (1977).
3. M. M. Nagels, T. A. Rijken and J. J. de Swart, Phys. Rev. D**15**, 2547 (1977).
4. V. I. Kukulin and V. M. Krasnopol'sky, J. Phys. G:Nucl. Part. Phys. **3**, 795 (1977).
5. Y. Suzuki and K. Varga, *Stochastic Variational Approach to Quantum-Mechanical Few-Body Problems*, Lecture Notes in Physics, Vol. m54 (Springer-Verlag, Berlin Heidelberg, 1998).
6. H. Nemura, Y. Akaishi and Y. Suzuki, Phys. Rev. Lett. **89**, 142504 (2002).
7. H. Nemura, et al.,Phys. Rev. Lett. **94**, 202502 (2005).
8. H. Takahashi, et al., Phys. Rev. Lett. **87**, 212502 (2001).
9. Khin Swe Myint, S. Shinmura and Y. Akaishi, Eur. Phys. J. A **16**, 21 (2003).
10. D. E. Lanskoy and Y. Yamamoto, Phys. Rev. C **69**, 014303 (2004).