Faddeev calculation of $^{6}_{\Lambda\Lambda}$He using SU$_6$ quark-model baryon-baryon interactions

Y. Fujiwara,[1,*] M. Kohno,[2] K. Miyagawa,[3] Y. Suzuki,[4] and J.-M. Sparenberg[5,6]
[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Physics Division, Kyushu Dental College, Kitakyushu 803-8580, Japan*
[3]*Department of Applied Physics, Okayama Science University, Okayama 700-0005, Japan*
[4]*Department of Physics, Niigata University, Niigata 950-2181, Japan*
[5]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[6]*Physique Nucléaire Théorique et Physique Mathématique, CP 229, Université Libre de Bruxelles, B-1050 Brussels, Belgium*
(Received 20 May 2004; published 28 September 2004)

Quark-model hyperon-nucleon and hyperon-hyperon interactions by the Kyoto-Niigata group are applied to the two-Λ plus α system in a three-cluster Faddeev formalism using two-cluster resonating-group method kernels. The model fss2 gives a reasonable two-Λ separation energy $\Delta B_{\Lambda\Lambda}=1.41$ MeV, which is consistent with the recent empirical value, $\Delta B^{\mathrm{exp}}_{\Lambda\Lambda}=1.01\pm 0.20$ MeV, deduced from the Nagara event. Some important effects that are not taken into account in the present calculation are discussed.

DOI: 10.1103/PhysRevC.70.037001 PACS number(s): 21.45.+v, 13.75.Ev, 21.80.+a, 12.39.Jh

A discovery of the double Λ hypernuclei, $^{6}_{\Lambda\Lambda}$He, called the Nagara event [1] has provided an invaluable source of information for the strength of the $\Lambda\Lambda$ interaction. Before this discovery, it had been believed that the two-Λ separation energy measured by $\Delta B_{\Lambda\Lambda}=B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He})-2B_{\Lambda}(^{5}_{\Lambda}\mathrm{He})$ or equivalently by $2E(^{5}\mathrm{He})-E(^{6}_{\Lambda\Lambda}\mathrm{He})-E(^{4}\mathrm{He})$ was fairly large, $\Delta B_{\Lambda\Lambda}\sim 4.3$ MeV, which implies that the $\Lambda\Lambda$ interaction is more attractive than the corresponding $^{1}S_{0}$ ΛN interaction. It was argued in Ref. [2] that the proper treatment of the $\Lambda\Lambda$-ΞN coupling effect in the $\Lambda\Lambda\alpha$ model is important to reproduce this $\Delta B_{\Lambda\Lambda}$ value in the coupled-channel AGS formalism using the ^{1}S $\Lambda\Lambda$ interaction of the Nijmegen model D. Now it is clear that the Nijmegen model D is not appropriate to describe the double Λ hypernuclei. Almost unique identification of the sequential decay processes involved in the Nagara event enforced it necessary to reanalyze the previous three events of the double Λ hypernuclei [3–5] and led to the conclusion that the $\Lambda\Lambda$ interaction is actually weakly attractive, under the assumption of possible involvement of excited states in the intermediate processes. The $\Delta B_{\Lambda\Lambda}$ value deduced from the Nagara event is 1.01 ± 0.20 MeV [1].

Based on this experimental information, several calculations have been carried out to determine the strength of the $\Lambda\Lambda$ interaction precisely and to find an appropriate interaction model mainly among the meson-theoretical Nijmegen models. For example, Filikhin, Gal, and Suslov [6] performed detailed Faddeev calculations using the $\Lambda\Lambda\alpha$ cluster model with many phenomenological $\Lambda\Lambda$ interactions and the so-called Isle $\Lambda\alpha$ potential with a repulsion core. They used the S-wave $\Lambda\alpha$ and $\Lambda\Lambda$ potentials for all the allowed partial waves. Since $^{6}_{\Lambda\Lambda}$He is essentially an S-wave dominant system, their approximation is legitimate. Nevertheless, the Nijmegen soft-core model NSC97e [7] was found to have too weak $\Lambda\Lambda$ interaction, corresponding to $\Delta B_{\Lambda\Lambda}\sim 0.66$ MeV [6].

We have discussed in Ref. [8] that the cluster model calculation with the α cluster needs a special care with an important rearrangement effect originating mainly from the starting energy dependence of the G-matrix interaction, when we consider composite-particle interactions starting from bare baryon-baryon interactions. For example, the energy loss of the interaction term in ^{4}He due to the added Λ particle is estimated to be 2.5–2.9 MeV in the model-independent way. This effect plays a major role to explain the well-known overbinding phenomena of the $^{5}_{\Lambda}$He. This effect is renormalized in usual $\Lambda\alpha$ potentials by fitting the Λ separation energy $B_{\Lambda}(^{5}_{\Lambda}\mathrm{He})=3.12\pm 0.02$ MeV. In the $\Lambda\Lambda\alpha$ system, however, there still remains an unrenormalizable effect mainly originating from the starting energy dependence of the ΛN interaction, which is found to be a repulsive effect of about 1 MeV [8]. As the result, the S-state matrix element of the $\Lambda\Lambda$ interaction is not $-\Delta B_{\Lambda\Lambda}\sim -1$ MeV, but should be more attractive than -2 MeV. From this argument, we can conclude that the $^{1}S_{0}\Lambda\Lambda$ interaction of NSC97e is by far too weak, and there is no meson-theoretical models available to explain the Nagara event.

The purpose of this brief report is to show the extent how our quark-model baryon-baryon interaction fss2 [9,10] can give a consistent description of the ΛN and $\Lambda\Lambda$ interactions with the available experimental data of light single- and double-Λ hypernuclei. The model fss2 describes all the available nucleon-nucleon (NN) and hyperon-nucleon (YN) scattering data, by incorporating the effective meson-exchange potentials at the quark level. It is now extended to the arbitrary two-baryon systems of the octet baryons without introducing any extra parameters [10]. The strangeness $S=-2$ sector, in particular, involves several important aspects of the baryon-baryon interactions. First it contains the $\Lambda\Lambda$ interaction, whose knowledge is essential to understand the binding mechanism of the double-Λ hypernuclei. The second is that the isospin $T=0$ system corresponds to the so-called H-particle channel, in which a strong attraction is expected from the color-magnetic interaction of the quark model. The third is the existence of the Pauli-forbidden state at the quark level, with the SU_3 quantum number $(11)_s$. The existence of such Pauli-forbidden state usually implies a strong repulsion

*Electronic address: fujiwara@ruby.scphys.kyoto-u.ac.jp

in some particular channels. It is therefore important to deal with the effect of the Pauli principle properly in the quark-model baryon-baryon interactions. Here we carry out Faddeev calculations of the $\Lambda\Lambda\alpha$ system, by directly using the quark-model baryon-baryon interactions in the strangeness $S=-2$ sector, and show that the $\Lambda\Lambda$ interaction of fss2 is consistent with the Nagara event after several corrections which are not easily incorporated in the present calculation.

The three-cluster Faddeev formalism used here is recently developed for general three-cluster systems interacting via two-cluster resonating-group method (RGM) kernels [11,12]. A nice point of this formalism is that the underlying NN, YN, and hyperon-hyperon (YY) interactions are more directly related to the structure of the hypernuclei than the models assuming simple two-cluster potentials. The reliability of this formalism is already confirmed in several systems; i.e., the three-nucleon bound state [13], the hypertriton [14], the 3α and $\Lambda\alpha\alpha$ systems [15]. The last application involves an effective ΛN force, called the SB force, which is a simple two-range Gaussian potential generated from the phase-shift behavior of fss2, by using an inversion method based on supersymmetric quantum mechanics [16]. It is given by

$$v\left({}^1E\right) = -\,128.0\ \exp(-\,0.8908\ r^2) + 1015\ \exp(-\,5.383\ r^2),$$

$$v\left({}^3E\right) = -\,56.31\ f\ \exp(-\,0.7517\ r^2) + 1072\ \exp(-\,13.74\ r^2), \tag{1}$$

where r is the relative distance between Λ and N in fm and the energy is measured in MeV. The odd interaction is assumed to be zero (pure Serber type). We generate the $\Lambda\alpha$ potential by folding these with the simple $(0s)^4$ shell-model wave function of the α cluster. In Eq. (1) an adjustable parameter f is introduced to circumvent the overbinding problem of ${}^5_\Lambda$He. The value $f=0.8923$ is necessary to reproduce the empirical value $B_\Lambda({}^5_\Lambda\mathrm{He})=3.120$ MeV, when the harmonic oscillator width parameter of the α cluster is assumed to be $\nu=0.257\ \mathrm{fm}^{-2}$. By using this ΛN force and the $\alpha\alpha$ RGM kernel generated from the three-range Minnesota force, we have shown in Ref. [15] that the mutually related, $\alpha\alpha$, 3α, and $\alpha\alpha\Lambda$ systems are well reproduced in terms of a unique set of the baryon-baryon interactions. In particular, the ground-state and excitation energies of ${}^9_\Lambda$Be are reproduced within $100\sim200$ keV accuracy.

The total wave function of the $\Lambda\Lambda\alpha$ system is expressed as the superposition of two independent Faddeev components ψ and φ: $\Psi=\psi+(1-P_{12})\varphi$. The two Λ particles are numbered 1 and 2, the α-cluster is numbered 3. The Faddeev equations read

$$\psi = G_0\widetilde{T}_{\Lambda\Lambda}(\varepsilon_{\Lambda\Lambda})(1-P_{12})\varphi,$$

$$\varphi = G_0 T_{\Lambda\alpha}(\psi - P_{12}\varphi). \tag{2}$$

Here, $\widetilde{T}_{\Lambda\Lambda}(\varepsilon_{\Lambda\Lambda})$ is the $\Lambda\Lambda$ component of the redundancy-free $\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ $\widetilde{T}$ matrices in the specific channel with the strangeness $S=-2$ and the isospin $T=0$. These T matrices are generated from the RGM kernel of the YY interaction, $V^{\mathrm{RGM}}_{YY}(\varepsilon_{YY})$, by solving the full coupled-channel Lippmann-Schwinger equation in the momentum space. The elimination of the Pauli-forbidden state with the SU_3 quantum number $(11)_s$ is automatically taken care of, simply by using the "RGM" T matrix, $\widetilde{T}_{\Lambda\Lambda}(\varepsilon_{\Lambda\Lambda})$, according to the prescription given in Ref. [11]. The total wave function Ψ is orthogonal to this Pauli-forbidden state, if we formulate a full coupled-channel Faddeev equation for the $\Lambda\Lambda\alpha$-$\Xi N\alpha$-$\Sigma\Sigma\alpha$ system. Such a calculation is not feasible for the time being, since we also need the $N\alpha$, $\Xi\alpha$, and $\Sigma\alpha$ interactions. Here we simply use the $\Lambda\Lambda$ component of the redundancy-free $\widetilde{T}$ matrix. The energy dependence involved in the RGM kernel and the $\widetilde{T}$ matrix is treated self-consistently by calculating the matrix elements of the (quark-model) $\Lambda\Lambda$ Hamiltonian as

$$\varepsilon_{\Lambda\Lambda} = \langle\Psi|h_{\Lambda\Lambda} + V^{\mathrm{RGM}}_{\Lambda\Lambda}(\varepsilon_{\Lambda\Lambda})|\Psi\rangle. \tag{3}$$

The detailed prescription for the energy dependence of the RGM kernel and the Pauli-forbidden state in the quark-model baryon-baryon interaction is given in Ref. [14]. A Faddeev formalism involving two identical particles (or clusters) is spelled out in Ref. [15].

Since we are interested in the $J^\pi=0^+$ ground state with the isospin $T=0$, the channel specification scheme of the $\Lambda\Lambda\alpha$ system is very simple. It becomes even simpler if we introduce no noncentral forces since the $\Lambda\alpha$ interaction is known to involve a very weak spin-orbit force. In the $(\Lambda\Lambda)-\alpha$ channel, the exchange symmetry of the two Λ's requires $(-)^{\lambda+S}=1$, where λ and S are the relative orbital angular-momentum and spin values of the two-Λ subsystem. The possible two-Λ states are therefore ${}^1\lambda_\lambda$ (λ=even) for $S=0$ and ${}^3\lambda_\lambda$ (λ=odd) for $S=1$. If we neglect noncentral forces, the spin value S and the total orbital angular-momentum quantum number L are good quantum numbers, and only ${}^1S_0$, ${}^1D_2$, ${}^1G_4$, ... states of the $\Lambda\Lambda$ interaction contribute in the ground state with $L=S=0$. Note that the orbital angular-momentum of the α particle, ℓ, is equal to λ since $J=0$. Similarly, in the $(\Lambda\alpha)$-Λ channel, the relative angular-momentum of the $\Lambda\alpha$ subsystem, ℓ_1, is equal to the orbital angular momentum of the spectator Λ, ℓ_2, because of the parity conservation and the possible spin value, $S=0$ or 1. These simplifications are of course the result of the channel truncation that we do not include the coupling to the possible $\Xi N\alpha$ and $\Sigma\Sigma\alpha$ configurations, in the present $\Lambda\Lambda\alpha$ model space. All the partial waves up to λ_{max}-$\ell_{1\mathrm{max}}$=6-6 are included for $\lambda=\ell$ and $\ell_1=\ell_2$. The momentum discretization points with n_1-n_2-n_3=10-10-5 in the previous notation [15] are used for solving the Faddeev equations. This ensures 1 keV accuracy.

Table I shows the $\Delta B_{\Lambda\Lambda}$ values in MeV, predicted by various combinations of the ΛN and $\Lambda\Lambda$ interactions. Here, we also show results of the other ΛN effective potentials and a simple three-range Gaussian potential, $V_{\Lambda\Lambda}$(Hiyama), used in Ref. [17]. We find that this $\Lambda\Lambda$ potential and the RGM T matrix for the old version of our quark-model interaction FSS [18] yield very similar results with the large $\Delta B_{\Lambda\Lambda}$ values about 3.6 MeV, since the $\Lambda\Lambda$ phases shifts predicted by these interactions increase up to about 40°. The improved quark model fss2 yields $\Delta B_{\Lambda\Lambda}=1.41$ MeV for the SB ΛN potential. The energy gain or loss due to the expansion of the

TABLE I. Comparison of $\Delta B_{\Lambda\Lambda}$ values in MeV, predicted by various $\Lambda\Lambda$ interactions and $V_{\Lambda N}$ potentials. The $\Lambda\Lambda$ potential $V_{\Lambda\Lambda}$(Hiyama) is the three-range Gaussian potential used in Ref. [17], and $V_{\Lambda\Lambda}$(SB) the two-range Gaussian potential given in Eq. (4). FSS and fss2 use the $\Lambda\Lambda$ RGM T matrix in the free space, with $\varepsilon_{\Lambda\Lambda}$ being the $\Lambda\Lambda$ expectation value determined self-consistently. For NS-JB $V_{\Lambda N}$ potentials, see Refs. [15,17]. $\Delta B^{\rm exp}_{\Lambda\Lambda} = 1.01 \pm 0.20$ MeV [1].

$V_{\Lambda\Lambda}$	Hiyama	FSS		fss2		SB
$V_{\Lambda N}$	$\Delta B_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$	$\varepsilon_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$	$\varepsilon_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$
SB	3.618	3.657	5.124	1.413	5.938	1.910
NS	3.548	3.630	5.151	1.366	5.947	1.914
ND	3.181	3.237	4.479	1.288	5.229	1.645
NF	3.208	3.305	4.622	1.271	5.407	1.713
JA	3.370	3.473	4.901	1.307	5.702	1.824
JB	3.486	3.599	5.141	1.327	5.952	1.911

partial waves from the S-wave to the I-wave is 35 ~ -50 keV, depending on the weakly attractive or repulsive nature of the P-wave ΛN force. In Table I, results are also shown for $V_{\Lambda\Lambda}$(SB), which is a two-range Gaussian potential generated from the $^1S_0$ $\Lambda\Lambda$ phase shift of fss2, by using the supersymmetric inversion method [16]. This potential is given by

$$V_{\Lambda\Lambda}(\mathrm{SB}) = -103.9 \exp(-1.176\, r^2) + 658.2 \exp(-5.936\, r^2), \tag{4}$$

where r is the relative distance between two Λ's in fm and the energy in MeV. This potential reproduces the low-energy behavior of the $\Lambda\Lambda$ phase shift of fss2 quite well, as seen in Fig. 1. We use this for all even partial waves and set the odd components zero by assuming the pure Serber type. [The odd components of the $\Lambda\Lambda$ interaction give no contribution to the present calculation in the LS coupling scheme anyway.] We find that this $\Lambda\Lambda$ potential yields larger $\Delta B_{\Lambda\Lambda}$ values than the fss2 RGM T-matrix by 0.36–0.58 MeV. We think that this difference of around 0.5 MeV between our fss2 result and the $V_{\Lambda\Lambda}$(SB) result is probably because we neglected the

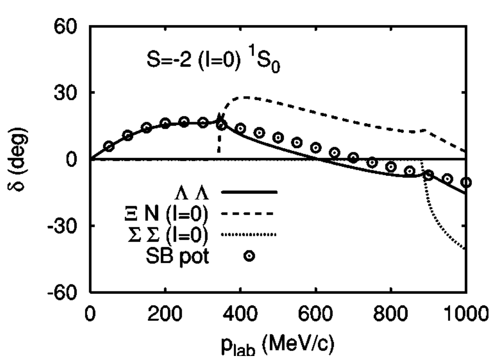

FIG. 1. $^1S_0$ phase shifts, predicted by fss2, in the $\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ coupled-channel system with the isospin $I=0$. The single-channel phase shift of the $\Lambda\Lambda$ scattering, predicted by the SB potential, is also shown in circles.

TABLE II. Decomposition of the ground-state energy of $^{\ 6}_{\Lambda\Lambda}$He (E), and the $\Lambda\Lambda$ ($\varepsilon_{2\Lambda}$) and $\Lambda\alpha$ ($\varepsilon_{\Lambda\alpha}$) expectation values to the kinetic- and potential-energy contributions. The SB ΛN force is used. The unit is in MeV. The experimental value is $E^{\rm exp} = -7.25 \pm 0.19$ MeV [1].

$V_{\Lambda\Lambda}$	kinetic +potential =total
Hiyama	$E = 21.328 - 31.186 = -9.858$
	$\varepsilon_{2\Lambda} = 11.869 - 6.779 = 5.089$
	$\varepsilon_{\Lambda\alpha} = 10.388 - 12.203 = -1.815$
FSS	$E = 20.179 - 30.076 = -9.897$
	$\varepsilon_{2\Lambda} = 10.800 - 5.676 = 5.124$
	$\varepsilon_{\Lambda\alpha} = 9.927 - 12.200 = -2.274$
fss2	$E = 17.111 - 24.764 = -7.653$
	$\varepsilon_{2\Lambda} = 8.567 - 2.628 = 5.938$
	$\varepsilon_{\Lambda\alpha} = 8.553 - 11.068 = -2.515$
SB	$E = 17.439 - 25.589 = -8.150$
	$\varepsilon_{2\Lambda} = 8.483 - 2.399 = 6.083$
	$\varepsilon_{\Lambda\alpha} = 8.774 - 11.595 = -2.821$

coupled-channel effects of the $\Lambda\Lambda\alpha$ channel to the $\Xi N\alpha$ and $\Sigma\Sigma\alpha$ channels. In our previous Faddeev calculation for ^{3}H [13], the energy gain due to the increase of the partial waves from the 2-channel (S-wave only) to 5-channel ($S+D$ waves) calculations is 0.36–0.38 MeV (see Table III of Ref. [13]). We should keep in mind that in all of these three-cluster calculations the Brueckner rearrangement effect of the α-cluster with the magnitude of about 1 MeV (repulsive) is very important [8]. It is also reported in Ref. [19] that the quark Pauli effect between the α cluster and the Λ hyperon yields a non-negligible repulsive contribution of 0.1–0.2 MeV for the Λ separation energy of $^{\ 6}_{\Lambda\Lambda}$He, even when a rather compact ($3q$) size of $b \sim 0.6$ fm is assumed as in our quark-model interactions. Taking all of these effects into consideration, we can conclude that the present results by fss2 are in good agreement with the experimental value, $\Delta B^{\rm exp}_{\Lambda\Lambda} = 1.01 \pm 0.20$ MeV, by the Nagara event [1].

Table II lists the energy decomposition to kinetic- and potential-energy contributions for the SB ΛN force. We find that the $\Lambda\Lambda$ potential matrix element in fss2 is $-2.4 \sim -2.6$ MeV, which is much weaker than that of FSS and the Hiyama potential ($-6 \sim -7$ MeV). This is consistent with the ($0s$) matrix element of the $\Lambda\Lambda$ G-matrix of fss2 [8], $\langle (0s)^2 | G_{\Lambda\Lambda} | (0s)^2 \rangle = -2.95$ MeV, obtained for the free-space G-matrix calculation with $\nu = 0.25$ fm^{-2}. For the normal nucleon density, $\rho_0 = 1.35$ fm^{-1}, this value is slightly reduced to -2.83 MeV. If ρ_0 is also assumed for Λ, it is further reduced to -2.63 MeV. If we compare the $\Lambda\alpha$ kinetic-energy matrix elements in fss2 (8.553 MeV) and in $V_{\Lambda\Lambda}$(SB) (8.774 MeV) with that of the $E(^9_\Lambda\mathrm{Be})$ system in Ref. [15], 9.215 MeV [see Eq. (30) of Ref. [15]], the latter is a little larger since the Λ is more strongly attracted by the two α clusters. The $\varepsilon_{\Lambda\alpha}$ value $-2.5 \sim -2.8$ MeV in Table II should be compared with the free value -3.12 MeV in $^5_\Lambda$He, but the decomposition to the kinetic-energy and potential-energy contributions is fairly different since $E_{\Lambda\alpha}=3.854-6.974=-3.120$ MeV in ${}^{5}_{\Lambda}$He.

The G-matrix calculation of fss2 also shows that the channel coupling effect to the $\Lambda\Lambda$ matrix element is 0.5 ~ 1 MeV, and the Pauli blocking effect of the ΞN channel is about 0.2 MeV. The latter is almost half of the 0.43 MeV, claimed in Ref. [20]. We can also carry out the Faddeev calculation by switching off the channel coupling in the T-matrix calculations. The results for the fss2 $\Lambda\Lambda$ and SB ΛN model are $\Delta B_{\Lambda\Lambda}=1.141$ MeV for the $\Lambda\Lambda$ single-channel calculation and 1.454 MeV for the $\Lambda\Lambda$-ΞN double-channel calculation. The energy gain by the full coupled-channel T-matrix calculation is only 0.27 MeV. However, such truncation of channels spoils the exact treatment of the Pauli principle, and the RGM T matrix does not satisfy the orthogonality condition to the Pauli forbidden $(11)_s$ state.

Summarizing this work, we have applied the quark-model YN and YY interactions, fss2 [9,10] and FSS [18], to the Faddeev calculation of the $\Lambda\Lambda\alpha$ system for ${}^{6}_{\Lambda\Lambda}$He, in the new three-cluster Faddeev formalism using two-cluster RGM kernels. The $\Lambda\alpha$ T matrix is generated from the ΛN effective force, which is derived from the ${}^{1}S_0$ and ${}^{3}S_1$ ΛN phase shifts of fss2 by the supersymmetric inversion method [16]. With a single adjustable parameter, this ΛN force gives a realistic description of the ${}^{5}_{\Lambda}$He and ${}^{9}_{\Lambda}$Be systems [15]. The $\Lambda\Lambda$ interaction of the quark-model baryon-baryon interactions is therefore reliably examined by solving the RGM T matrix in the $\Lambda\Lambda$-$\Xi N-\Sigma\Sigma$ coupled-channel formalism, and by using it in the coupled-channel Faddeev equation. Here we have used only $\Lambda\Lambda\alpha$ configuration and obtained $\Delta B_{\Lambda\Lambda}=1.41$ MeV for fss2, as a measure of the two-Λ separation energy. A simple Gaussian $\Lambda\Lambda$ potential, reproducing the ${}^{1}S_0$ $\Lambda\Lambda$ phase shift of fss2, yields $\Delta B_{\Lambda\Lambda}=1.91$ MeV. Considering some repulsive effects from the Brueckner rearrangement of the α cluster ($\sim$1 MeV) [8] and the quark Pauli principle between the α cluster and the Λ hyperon ($\sim$0.1–0.2 MeV) [19], we can conclude that the present results by fss2 are in good agreement with the experimental value, $\Delta B^{\rm exp}_{\Lambda\Lambda}=1.01\pm0.20$ MeV, deduced from the Nagara event [1]. Together with previous several Faddeev calculations, we have found that the model fss2 gives reasonable descriptions of many three-body systems, including the three-nucleon bound state [13], the hypertriton [14], ${}^{9}_{\Lambda}$Be [15], and ${}^{6}_{\Lambda\Lambda}$He.

ACKNOWLEDGMENTS

This work was supported by Grants-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Science (JSPS) (Nos. 15540270, 15540284, and 15540292).

[1] H. Takahashi *et al.*, Phys. Rev. Lett. **87**, 212502 (2001).
[2] S. B. Carr, I. R. Afnan, and B. F. Gibson, Nucl. Phys. **A625**, 143 (1997).
[3] D. J. Prowse, Phys. Rev. Lett. **17**, 782 (1966).
[4] M. Danysz *et al.*, Phys. Rev. Lett. **11**, 29 (1963).
[5] S. Aoki *et al.*, Prog. Theor. Phys. **85**, 1287 (1991).
[6] I. N. Filikhin, A. Gal, and V. M. Suslov, Phys. Rev. C **68**, 024002 (2003).
[7] Th. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C **59**, 21 (1999).
[8] M. Kohno, Y. Fujiwara, and Y. Akaishi, Phys. Rev. C **68**, 034302 (2003).
[9] Y. Fujiwara, T. Fujita, M. Kohno, C. Nakamoto, and Y. Suzuki, Phys. Rev. C **65**, 014002 (2002).
[10] Y. Fujiwara, M. Kohno, C. Nakamoto, and Y. Suzuki, Phys. Rev. C **64**, 054001 (2001).
[11] Y. Fujiwara, H. Nemura, Y. Suzuki, K. Miyagawa, and M. Kohno, Prog. Theor. Phys. **107**, 745 (2002).
[12] Y. Fujiwara, Y. Suzuki, K. Miyagawa, M. Kohno, and H. Nemura, Prog. Theor. Phys. **107**, 993 (2002).
[13] Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, and H. Nemura, Phys. Rev. C **66**, 021001(R) (2002).
[14] Y. Fujiwara, K. Miyagawa, M. Kohno, and Y. Suzuki, Phys. Rev. C **70**, 024001 (2004).
[15] Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, D. Baye, and J.-M. Sparenberg, Phys. Rev. C **70**, 024002 (2004).
[16] J.-M. Sparenberg and D. Baye, Phys. Rev. C **55**, 2175 (1997).
[17] E. Hiyama, M. Kamimura, T. Motoba, T. Yamada, and Y. Yamamoto, Prog. Theor. Phys. **97**, 881 (1997); Phys. Rev. C **66**, 024007 (2002).
[18] Y. Fujiwara, C. Nakamoto, and Y. Suzuki, Phys. Rev. Lett. **76**, 2242 (1996); Phys. Rev. C **54**, 2180 (1996).
[19] Y. Suzuki and H. Nemura, Prog. Theor. Phys. **102**, 203 (1999).
[20] K. S. Myint, S. Shinmura, and Y. Akaishi, Eur. Phys. J. A **16**, 21 (2003).