# Baryonic mixing in double-strangeness $p$ shell hypernuclei

D.E. Lanskoy
*Institute of Nuclear Physics, Moscow State University*
*119992 Moscow, Russia*

**Abstract**

The $\Lambda\Lambda - \Xi N$ coupling in $p$ shell $\Lambda\Lambda$ hypernuclei exemplified by ${}^{12}_{\Lambda\Lambda}$Be is studied. Various Nijmegen meson-exchange potential models are used for the diagonal $\Lambda\Lambda$ and coupling $\Lambda\Lambda - \Xi N$ interactions. The coupling effect is considerably different in various hypernuclear states. It is maximal in the $1p^2_\Lambda(L = S = 0)$ state. Implications of the coupling effect for the rates of the $(K^-, K^+)$ reaction are discussed.

## 1 Introduction

Mixing of different baryonic states in non-strange nuclei as well as in hypernuclei has been discussed for a long time. Many theoretical studies addressed the $NN - \Delta N$ coupling in ordinary nuclei and the $\Lambda N - \Sigma N$ coupling in $\Lambda$ hypernuclei. Nevertheless, direct probing of these baryonic admixtures still remains an unresolved problem.

Probably, the $\Lambda\Lambda - \Xi N$ coupling in double-$\Lambda$ hypernuclei is the most significant among various baryonic couplings in nuclear systems due to the small (about 25 MeV) mass splitting between the $\Lambda\Lambda$ and $\Xi N$ pairs (compared to the 300 MeV splitting between $N$ and $\Delta$ and the 80 MeV splitting between $\Lambda$ and $\Sigma$). Importantly, the mass splitting is comparable with nuclear and hypernuclear binding effects. Therefore, actual energy differences between initial (non-mixed) hypernuclear $\Lambda\Lambda$ and $\Xi$ states substantially vary in different systems. Such diversity provides a chance to extract the mixing effect more or less unambiguously from relevant data. In many-body systems, the mass difference between ${}^{A}\mathrm{Z} + \Lambda + \Lambda$ and ${}^{A+1}\mathrm{Z}' + \Xi$ determines the mixing rather than the mass difference of free particles. For instance, the mixing is enhanced considerably in five-body hypernuclei ${}^{5}_{\Lambda\Lambda}$H and ${}^{5}_{\Lambda\Lambda}$He since the fourth nucleon appearing due to the $\Lambda\Lambda - \Xi N$ transition is bound exceptionally strongly in the $\alpha$ particle [1]. Moreover, the mixing in ${}^{5}_{\Lambda\Lambda}$He is stronger than that in ${}^{5}_{\Lambda\Lambda}$H due to the $\Xi^- - \Xi^0$ mass difference [1, 2]. This leads to an unusual many-body charge symmetry breaking effect, which can be an unambiguous signature of the baryonic mixing [2]. However, neither ${}^{5}_{\Lambda\Lambda}$H nor ${}^{5}_{\Lambda\Lambda}$He has been observed so far.

Expectedly, the five-body $\Lambda\Lambda$ hypernuclei provide the strongest $\Lambda\Lambda - \Xi N$ coupling, when one concerns with the *ground* states of $\Lambda\Lambda$ hypernuclei (strictly speaking, "$\Lambda\Lambda$ hypernucleus" means here a state of an $S = -2$ hypernucleus with *dominant* $\Lambda\Lambda$ component). But the excited $\Lambda\Lambda$ states are evidently closer in energy to the corresponding $\Xi$ hypernuclear spectrum, so the coupling can be enhanced. So far, only ground states of $\Lambda\Lambda$ hypernuclei have been observed [3, 4, 5, 6]. Probably, this is the main reason why the majority of theoretical studies of the $\Lambda\Lambda - \Xi N$ coupling in $\Lambda\Lambda$ hypernuclei [7, 8, 9, 10, 11, 12, 13, 14, 15] is restricted to the ground states (excepting Refs. [9, 11]).

We address here the hyperonic mixing in $p$ shell $\Lambda\Lambda$ hypernuclei and deal with the ground as well as *excited* states. The motivation of this study is at least twofold.

Contrary to the naive expectation basing on the small mass difference, all the earlier calculations [7, 8, 9, 10, 11] predicted relatively small effects of the $\Lambda\Lambda - \Xi N$ coupling in $\Lambda\Lambda$ hypernuclei. The reason was that the old Nijmegen hard-core D model [16] was employed for the $\Lambda\Lambda$ diagonal and coupling interactions. It was the unique meson-exchange model compatible with strong (4–5 MeV) attraction energy of the $\Lambda\Lambda$ pair deduced from the old experiments [3, 4]. Since Nagara event [5] it is commonly believed that the $\Lambda\Lambda$ attraction is much weaker. Therefore, the obsolete model should no more be treated as the best in the $S = -2$ sector. While other meson-exchange potential models [17, 18, 19, 20, 21] predict stronger $\Lambda\Lambda - \Xi N$ coupling, the effect was probably *underestimated* in the earlier studies.

The second motivation comes from the experimental side. So far, the $\Lambda\Lambda$ hypernuclei have been detected [3, 4, 5, 6] by their weak decays. These methods are obviously limited to the ground states only. Now J-PARC facility in Japan is under construction [22], where the experimental study of double-strangeness hypernuclei from the $(K^-, K^+)$ reaction in the counter experiment [23] is scheduled as the "day-one" experiment. In this experiment, the *whole spectrum* of the $S = -2$ hypernucleus can be generally seen. The project mostly concerns with $\Xi$ hypernuclei, which can be produced in the one-step $p(K^-, K^+)\Xi^-$ process from a proton inside a nucleus. The production of $\Lambda\Lambda$ hypernuclei seemingly requires a two-step process: $K^-p \to \pi^0\Lambda$, $\pi^0 p \to K^+\Lambda$, which reduces the cross sections substantially [24].

However, it was suggested [9] that the rates of the production of $\Lambda\Lambda$ hypernuclei may be enhanced just for states with large $\Xi^-$ admixtures. The admixture can serve as a *doorway* state for the one-step $p(K^-, K^+)\Xi^-$ process. Similar mechanism has been considered for production of neutron-rich $\Lambda$ hypernuclei via $\Sigma^-$ admixture [25]. The rate of the one-step mechanism is proportional to the probability of the admixture. Therefore, study of the $\Lambda\Lambda - \Xi N$ mixing is directly related to feasibility of the $(K^-, K^+)$ reaction for the production of $\Lambda\Lambda$ hypernuclei.

Here, we investigate the $\Lambda\Lambda - \Xi N$ coupling in $p$ shell $\Lambda\Lambda$ hypernuclei exemplified by ${}^{12}_{\Lambda\Lambda}\mathrm{Be}$, which is attainable in the $(K^-, K^+)$ reaction from the ${}^{12}\mathrm{C}$ target.

## 2 Model

We adopt the coupled-channel model similar to that previously applied [2] to the $s$ shell five-body hypernuclei.

Here, we deal with the ground state of ${}^{12}_{\Lambda\Lambda}\mathrm{Be}$, which main component is ${}^{10}\mathrm{Be}_{\mathrm{gs}} + \Lambda\Lambda(1s^2)$, and excited states of the ${}^{10}\mathrm{Be}_{\mathrm{gs}} + \Lambda\Lambda(1p^2)$ type. We choose this type of excited states among variety of other states ($1s_\Lambda 1p_\Lambda$, core-excited *etc*) at this stage since these states are, first, of a simple structure and, second, lie just near threshold ${}^{10}\mathrm{Be} + \Lambda + \Lambda$ and, therefore, much closer (by about 20 MeV) to the $\Xi$ hypernuclear states than the $\Lambda\Lambda$ ground state.

For the ground state ($0^+$), the $\Lambda\Lambda$ pair evidently possesses $L = S = 0$. For the excited states, $L = 0, 1, 2$ and $S = 0, 1, 0$ respectively, are possible. In the first and the last cases, we have the $0^+$ and $2^+$ state, respectively. At $L = 1$, three states $(0^+, 1^+, 2^+)$ appear, which are degenerated without the coupling.

The main admixture channel is expected to be ${}^{11}\mathrm{B}_{\mathrm{gs}} + \Xi^-$, where the hyperon is in a $p$ state. To simplify the problem and to take into account effectively also excited states of ${}^{11}\mathrm{B}$, we treat the $\Xi N$ pair in this channel as a pure $LS$ state. For the ground state, this is correct exactly in the framework of the single-particle model. For the excited states, the coupling effect can be overestimated to some extent, but no more than by several tens of per cent. Note that the $L = 1$ states remain nonsplitted under this approximation.

We check also the role of the third channel, namely, ${}^{11}_{\Xi}\mathrm{Z}_{\mathrm{gs}} + N$, where the $\Xi N$ pair possesses zero isospin, and the nucleon is in an $s$ state. The contribution of this channel is found to be small (10% or less as compared to the main admixture channel), but strongly dependent on input parameters. The suppression of this channel results from the orthogonality of the nucleon state to the $1s$ states inside the nuclear core. For definiteness, we discuss below the results obtained within the *two-channel* approximation neglecting the third channel. Other channels are supposed to be less important.

We use the Hartree-Fock approximation and come to the following set of coupled equations for radial wave functions $\varphi$ of $\Lambda$ and $\chi$ of $\Xi$ (for details, see [2]):

$$-\frac{1}{2\mu_\Lambda}\varphi'' + U_\Lambda\varphi = e\varphi - \sigma\chi, \tag{1}$$

$$-\frac{1}{2\mu_\Xi}\chi'' + U_\Xi\chi = (e - \Delta e)\chi - \sigma\varphi. \tag{2}$$

The threshold energy difference $\Delta e$ is calculated from the empirical binding energies of ${}^{10}\mathrm{Be}_{\mathrm{gs}}$ and ${}^{11}\mathrm{B}_{\mathrm{gs}}$. The potential acting on the $\Lambda$ hyperon, $U_\Lambda = U_{c\Lambda} + \langle\varphi\,|V_{\Lambda\Lambda}|\,\varphi\rangle$, includes the $\Lambda$-core interaction $U_{c\Lambda}$ and $\Lambda\Lambda$ diagonal potential $V_{\Lambda\Lambda}$. Since $\varphi$ is involved in $U_\Lambda$, the set of equations is essentially nonlinear as usual in Hartree-Fock problems. The coupling matrix element $\sigma$ appears from nondiagonal $\Lambda\Lambda - \Xi N$ interaction $V_{\Lambda\Lambda,\Xi N}$. At last, $\Xi^-$-core potential $U_\Xi$ is included.

For the hyperon-core potentials, we use phenomenological Woods-Saxon wells. The depth of the $\Xi^- + {}^{11}\mathrm{B}$ potential was estimated as 14 MeV from the $(K^-, K^+)$ experiments [26, 27]. Though the data are rather scarce and uncertain, there is no other relevant experimental information available and we adopt this value. Coulomb $\Xi^- + {}^{11}$B interaction is taken into account as well. For the $U_{c\Lambda}$ ($\Lambda + {}^{10}$Be) potential, we fit the depth to $\Lambda$ binding energy $B_\Lambda = 10.24 \pm 0.05$ MeV [28] of ${}^{11}_{\Lambda}\mathrm{B}_{\mathrm{gs}}$ (no data on ${}^{11}_{\Lambda}\mathrm{Be}_{\mathrm{gs}}$ are known). This potential gives the $1p$ state of $\Lambda$ lying slightly below the threshold.

For the two-body $\Lambda\Lambda$ diagonal and $\Lambda\Lambda - \Xi N$ coupling potentials $V_{\Lambda\Lambda}$ and $V_{\Lambda\Lambda,\Xi N}$, we use effective interactions derived [2] within the $G$ matrix procedure from various Nijmegen meson-exchange models. The set of effective interactions presented in [2] is complemented by the most recent model ESC03 [21, 29]. Just $G$ matrix effective interactions are consistent with our Hartree-Fock-type model and provide some effective account of admixtures of higher-lying states, which are not included to the two-channel problem explicitly (see [2]).

# 3 Results and discussion

We calculate two quantities revealing the coupling effect. The first one is $\Delta B_{\Lambda\Lambda}$, which is treated usually in studies of $\Lambda\Lambda$ hypernuclei as the $\Lambda\Lambda$ interaction energy. It is defined as

$$\Delta B_{\Lambda\Lambda}({}^{A+2}_{\Lambda\Lambda}\mathrm{Z}) = B_{\Lambda\Lambda}({}^{A+2}_{\Lambda\Lambda}\mathrm{Z}) - 2B_\Lambda({}^{A+1}_{\Lambda}\mathrm{Z}), \tag{3}$$

where $B_{\Lambda\Lambda}$ is the separation energy of the $\Lambda\Lambda$ pair, $B_\Lambda$ is the $\Lambda$ binding (separation) energy in the ground state of the corresponding single-$\Lambda$ hypernucleus. This definition is natural for ground states. For the excited $1p_\Lambda^2$ state, we *define*

$$\Delta B_{\Lambda\Lambda}({}^{A+2}_{\Lambda\Lambda}\mathrm{Z}, 1p_\Lambda^2) = B_{\Lambda\Lambda}({}^{A+2}_{\Lambda\Lambda}\mathrm{Z}, 1p_\Lambda^2) - 2B_\Lambda({}^{A+1}_{\Lambda}\mathrm{Z}, 1p_\Lambda), \tag{4}$$

which keeps the usual meaning of $\Delta B_{\Lambda\Lambda}$.

The second quantity is $\Xi$ admixture probability

$$p_\Xi = \int_0^\infty \chi^2 dr, \tag{5}$$

which cannot be directly observed in hypernuclear spectra, but can provide enhanced production rates via the doorway state (see Introduction).

First, we show $\Delta B_{\Lambda\Lambda}$ calculated in the *single-channel* approach without coupling (Equation (1) without the last term). In Table 1, the $\Delta B_{\Lambda\Lambda}$ in various states are shown for various Nijmegen potentials. As described in [2], all the diagonal $\Lambda\Lambda$ potentials are fitted to $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 1.0$ MeV according to Nagara event [5]. It is seen that $\Delta B_{\Lambda\Lambda}$ for the ground state is greater than that in ${}^{6}_{\Lambda\Lambda}$He, thus $\Delta B_{\Lambda\Lambda}$ increases with $A$ in this $A$ region (this is not the case in heavier systems [30]). In the excited states, $\Delta B_{\Lambda\Lambda}$ is small since $\Lambda$ hyperons in loosely bound states move rather far from each other and interact relatively weakly. It is seen that $\Delta B_{\Lambda\Lambda}$ depends on $L$ only slightly, therefore, the excited states are nearly degenerated in the single-channel approximation. Note that distinctions between various models are not high in the single-channel approximation.

Table 1: $\Delta B_{\Lambda\Lambda}$ (MeV) in the single-channel approximation for various states of ${}^{12}_{\Lambda\Lambda}$Be calculated with various Nijmegen potentials.

| Potential | ground state | $1p_\Lambda^2(L=0)$ | $1p_\Lambda^2(L=1)$ | $1p_\Lambda^2(L=2)$ |
|---|---|---|---|---|
| NHC-D [16] | 1.34 | 0.36 | 0.39 | 0.36 |
| NSC97f [19, 20] | 1.39 | 0.40 | 0.34 | 0.37 |
| NSC97e [19, 20] | 1.38 | 0.39 | 0.36 | 0.36 |
| NSC89 [18] | 1.63 | 0.58 | 0.19 | 0.34 |
| ESC03 [21, 29] | 1.44 | 0.43 | 0.14 | 0.35 |
| NHC-F [17] | 1.63 | 0.58 | 0.19 | 0.34 |

Evidently, the coupling effect is revealed in differences between the full (two-channel) and single-channel results. In Fig. 1, $\Delta B_{\Lambda\Lambda}$ values (left panel) and $\Xi$ channel probabilities $p_\Xi$ (right panel) calculated in the *full* (two-channel) model are presented for various Nijmegen models as functions of volume integral $\int d^3r V_{\Lambda\Lambda,\Xi N}$, which is a natural measure of the coupling strength [2]. First, it is seen that the contribution

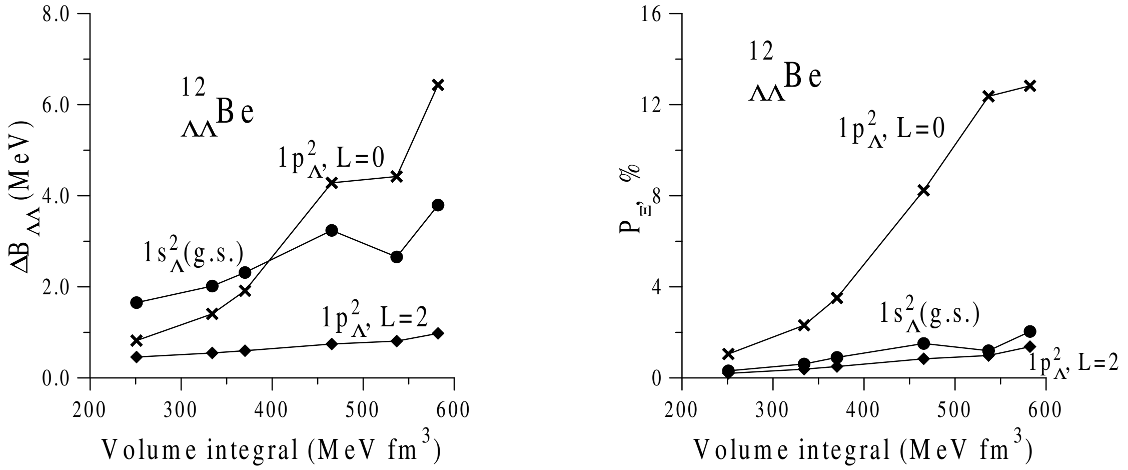


Figure 1: $\Delta B_{\Lambda\Lambda}$ (left) and $\Xi$ admixture probabilities (right) in ${}^{12}_{\Lambda\Lambda}$Be as functions of $\int d^3 r V_{\Lambda\Lambda,\Xi N}$. Diagonal $\Lambda\Lambda$ and coupling $\Lambda\Lambda - \Xi N$ potentials are from Nijmegen models (from left to right) NHC-D [16], NSC97f, NSC97e [19, 20], NSC89 [18], ESC03 [21, 29] and NHC-F [17].

of the coupling interaction to the energy of the ground state may be considerable. For instance, the $\Delta B_{\Lambda\Lambda}$ values for the weakest coupling (Nijmegen hard-core D model, the leftmost point) and for the strongest coupling (Nijmegen hard-core F model, the rightmost point) differ by about 2 MeV. In the latter case, $\Delta B_{\Lambda\Lambda}$ is as large as almost 4 MeV (compare with the single-channel calculation, Table 1, and recall that all the interactions are fitted to the same value $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 1$ MeV). On the other hand, the $\Xi$ probability in the ground state is not substantially greater than 1% anyway.

A stronger coupling effect is expected in the $1p^2_\Lambda$ states since they lie much closer in energy to the $\Xi$ hypernuclear spectrum. It is seen in Fig. 1 that this is just the case for the $L = S = 0$ state: $\Delta B_{\Lambda\Lambda}(1p^2_\Lambda)$ for strong coupling potentials exceeds the ground state value. For the strongest coupling, $\Delta B_{\Lambda\Lambda}$ reaches a huge value about 6 MeV. Contrary to the ground state, the $\Xi$ admixture probabilities may be also rather great.

On the other hand, the coupling effect is relatively small for the $L = 2$ state and extremely small for the $L = 1$ state (the latter is not shown in Fig. 1 since $\Delta B_{\Lambda\Lambda}$ values almost coincide with those in Table 1). So the coupling splits levels almost degenerated without it. Whereas the $\Delta B_{\Lambda\Lambda}$ energies in the $L = 1$ and $L = 2$ states are determined mainly by the diagonal interaction, the coupling contributes dominantly to $\Delta B_{\Lambda\Lambda}(L = 0)$.

Without the coupling or at weak coupling potentials, $\Delta B_{\Lambda\Lambda}$ in the ground state is greater than that in the $1p^2_\Lambda$ states. This looks natural since the $\Lambda\Lambda$ pair interacts stronger when it is bound tighter and hyperons move closer to each other. However, for stronger couplings we observe the opposite relation: $\Delta B_{\Lambda\Lambda}(1p^2_\Lambda) > \Delta B_{\Lambda\Lambda}(1s^2_\Lambda)$. Since the $1p^2_\Lambda$ states are closer in energy to the $\Xi$ hypernuclear spectrum, the main contribution to the $\Lambda\Lambda$ interaction energy is originated from the coupling. This unusual relation between $\Delta B_{\Lambda\Lambda}(1s^2_\Lambda)$ and $\Delta B_{\Lambda\Lambda}(1p^2_\Lambda)$ can be a convincing signature of the $\Xi$ admixture in $\Lambda\Lambda$ hypernuclei.

# 4 Conclusion and outlook

Continuing our study of the $\Lambda\Lambda - \Xi N$ coupling in $\Lambda\Lambda$ hypernuclei [2], we extend the consideration to the $p$ shell systems. It is shown that the effect is meaningful both in the ground and excited states. Depending on the unknown $\Lambda\Lambda - \Xi N$ potential, it can be an important factor determining $\Lambda\Lambda$ hypernuclear spectra. The size of the coupling depends strongly on quantum numbers of the excited states and can split levels degenerated or almost degenerated without the coupling.

Usually, the mixing effects in nuclear as well as hypernuclear systems are hardly extracted from experimental data since some alternative descriptions or "background" effects are possible (see discussion in [2]). Unusual relation between $\Delta B_{\Lambda\Lambda}(1s_\Lambda^2)$ and $\Delta B_{\Lambda\Lambda}(1p_\Lambda^2)$ unlikely can be obtain in any single-channel consideration and can serve as a signature of the coupling.

One cannot predict probabilities of the baryonic admixtures unambiguously now since a lot of poorly known phenomenological inputs are involved in the calculations and, most importantly, the coupling potential is unknown. But it is shown here that the $\Xi$ admixtures can exceed 10% at favorable conditions. Obviously, the probabilities can be further magnified in the calculations by varying of some parameters, for instance, by reducing of the energy separation of initial (nonmixed) states. Such conditions maybe really achieved in some other $p$ shell hypernuclei, though due to mentioned uncertainties we cannot try now to establish what hypernuclei and what states are most promising. But it may be suggested that some excited states in $p$ shell $\Lambda\Lambda$ hypernuclei incorporate comparable weights of $\Lambda\Lambda$, $\Xi N$ (and, maybe, $\Sigma\Sigma$) components. Search for such states of "dibaryonic" type is a rather exciting task. It relates to some extent to the long history of $H$ dihyperon [31], but we mean here states appearing only due to the nuclear environment.

Large $\Xi$ admixtures generally imply relatively large production rates in the $(K^-, K^+)$ reaction via $\Xi^-$ doorway states and the one-step $K^-p \to K^+\Xi^-$ process [9]. However, the production rate for the specific $1p_\Lambda^2(L=0)$ state in ${}^{12}_{\Lambda\Lambda}$Be is expectedly small since the $0^+ \to 0^+$ transition is strongly suppressed in the $(K^-, K^+)$ reaction due to a large momentum transfer. Search for $\Lambda\Lambda$ hypernuclear states with considerable $\Xi$ admixtures and yet producible with reasonable rates is also a challenging problem.

This study is restricted to the states with dominant $\Lambda\Lambda$ component ($\Lambda\Lambda$ hypernuclei). On the other hand, the same $\Lambda\Lambda - \Xi N$ interaction can shift levels of $\Xi$ hypernuclei and generate their widths due to the $\Xi N \to \Lambda\Lambda$ conversion. Now any information on $\Xi$ hypernuclear spectra and widths is absent. Complex investigation of the spectra of $S = -2$ hypernuclei feasible in future experiments [23] together with adequate theoretical studies can provide certain understanding of baryonic interactions in the $S = -2$ sector.

## Acknowledgement

I am grateful to Y. Yamamoto, my collaborator in study of hyperonic mixing in double-strangeness hypernuclei. The work was supported partially by Russian National Program for leading scientific schools, Grant 1619.2003.2.

## References

[1] Khin Swe Myint, Y. Akaishi, Prog.Theor.Phys. Suppl. 117 (1994) 251; Khin Swe Myint, S. Shinmura, Y. Akaishi, Eur.Phys.J. A16 (2003) 21

[2] D.E. Lanskoy, Y. Yamamoto, Phys.Rev. C69 (2004) 014303; in: QFTHEP2003, *Proceedings of the XVII International Workshop on High Energy Physics and Quantum Field Theory*, ed. by M. Dubinin, V. Savrin (Moscow, 2004), p.485

[3] R.H. Dalitz, D.H. Davies, P.H. Fowler, A. Montwill, J. Pniewski, J.A. Zakrzewski, Proc.R.Soc. London, A426 (1989) 1

[4] S. Aoki *et al.*, Prog.Theor.Phys. 85 (1991) 1287

[5] H. Takahashi *et al.*, Phys.Rev.Lett. 87 (2001) 212502; K. Nakazawa, in: QFTHEP2003, *Proceedings of the XVII International Workshop on High Energy Physics and Quantum Field Theory*, ed. by M. Dubinin, V. Savrin (Moscow, 2004), p.493

[6] J.K. Ahn *et al.*, Phys.Rev.Lett. 87 (2001) 132504

[7] Y. Yamamoto, T. Motoba, H. Himeno, K. Ikeda, S. Nagata, Prog.Theor.Phys. Suppl. 117 (1994) 361
[8] B.F. Gibson, I.R. Afnan, J.A. Carlson, D.R. Lehman, Prog.Theor.Phys. Suppl. 117 (1994) 339
[9] C.B. Dover, A. Gal, D.J. Millener, Nucl.Phys. A572 (1994) 85
[10] S.B. Carr, I.R. Afnan, B.F. Gibson, Nucl.Phys. A625 (1997) 143
[11] T. Yamada, C. Nakamoto, Phys.Rev. C62 (2000) 034319
[12] I.R. Afnan, B.F. Gibson, Phys.Rev. C67 (2003) 017001
[13] T. Yamada, Phys.Rev. C69 (2004) 044301
[14] I. Vidaña, A. Ramos, A. Polls, Phys.Rev. C70 (2004) 024306
[15] H. Nemura, S. Shinmura, Y. Akaishi, Khin Swe Myint, nucl-th/0407033
[16] M.M. Nagels, T.A. Rijken, J.J. de Swart, Phys.Rev. D15 (1977) 2547
[17] M.M. Nagels, T.A. Rijken, J.J. de Swart, Phys.Rev. D20 (1979) 1633
[18] P.M.M. Maessen, Th.A. Rijken, J.J. de Swart, Phys.Rev. C40 (1989) 2226
[19] Th.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys.Rev. C59 (1999) 21
[20] V.G.J. Stoks, Th.A. Rijken, Phys.Rev. C59 (1999) 3009
[21] Th.A.Rijken, in: QFTHEP2003, *Proceedings of the XVII International Workshop on High Energy Physics and Quantum Field Theory*, ed. by M. Dubinin, V. Savrin (Moscow, 2004), p.261 and These Proceedings
[22] http://j-parc.jp/index.html
[23] K. Imai *et al.*, Letter of Intent for new generation spectroscopy of hadron many-body systems with strangeness $S = -2$ and $-1$, KEK, 2002
[24] A.J. Baltz, C.B. Dover, D.J. Millener, Phys.Lett. B123 (1983) 9
[25] T.Yu. Tretyakova, D.E. Lanskoy, Nucl.Phys. A691 (2001) 51c
[26] T. Fukuda *et al.*, Phys.Rev. C58 (1998) 1306
[27] P. Khaustov *et al.*, Phys.Rev. C61 (2000) 054603
[28] D.H. Davis, J. Pniewsky, Contemp.Phys. 27 (1986) 91
[29] Th.A. Rijken, Y. Yamamoto, private communication
[30] D.E. Lanskoy, Yu.A Lurie, A.M. Shirokov, Z.Phys. A357 (1997) 95
[31] R.L. Jaffe, Phys.Rev.Lett. 38 (1977) 195