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Ξ hypernuclei predicted by the new interaction model ESC08

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Abstract. The features of the new interaction model ESC08 in ΛN, ΣN and ΞN channels are demonstrated by the partial wave contributions to single hyperon potentials $U_Y(Y = \Lambda, \Sigma, \Xi)$ in nuclear matter on the basis of the G-matrix theory. Ξ hypernuclei are studied with the ΞN G-matrix interactions derived from ESC08.

1 Introduction

The properties of baryon many-body systems, which contains not only nucleons but also hyperons with strangeness, link closely to the underlying hyperon(Y)-nucleon(N) interactions. As demonstrated in our previous works [1] [2], it is very important to test the YN interaction models in analyses of various hypernuclear phenomena. For such a purpose the G-matrix theory is very convenient. The features of free-space YN interactions are related to the properties of hypernuclei through the corresponding G-matrix interactions. These G-matrix interactions are considered as effective interactions used in the model spaces. Thus, the hypernuclear phenomena and the underlying YN interaction models are linked through the models of hypernuclei.

SU(3)-invariant interaction models give useful guidance toward an entire picture of strong interactions among octet baryons. Epoch-making development for such an approach has been accomplished by the Extended Soft Core (ESC) models, in which two-meson and meson-pair exchanges are taken into account explicitly and no effective boson is included differently from the usual one-boson exchange models. Recently, Th.A. Rijken, M.M. Nagels and Y.Y. have proposed the latest version the ESC08 [3]. In the parameter fitting of ESC08, the G-matrix results were used as an important guidance to impose constraints so that the resulting interaction model was consistent with the hypernuclear properties and especially gave the attractive ΞN sector substantially. The two versions ESC08a and ESC08b have been proposed. In this report, first the features of the ESC08 model in ΛN, ΣN and ΞN channels are demonstrated by the partial wave contributions to single hyperon potentials $U_Y(Y = \Lambda, \Sigma, \Xi)$ in nuclear matter on the basis of the G-matrix theory. Next, as an application of the attractive ΞN G-matrix interaction, some Ξ hypernuclei are studied with the four-body cluster models.

2 Λ, Σ and Ξ in nuclear matter

Here, we demonstrate the properties of the ΛN, ΣN and ΞN G-matrix interactions derived from ESC08a/b. For simplicity, here, the G-matrix equations are solved with the QTQ prescription (Gap choice), where no potential term is taken into account in intermediate propagations of correlated YN pairs. A two-particle state with isospin (T), spin (S), orbital and total angular momenta (L and J) is represented as $^{2T+1,2S+1}L_J$. An isospin quantum number is often omitted, when it is evident.

Table 1. $U_\Lambda(\rho_0)$ and partial wave contributions in $^{2S+1}L_J$ states.

	$^1S_0$	$^3S_1$	$^1P_1$	^3P	D	U_Λ
08a	−12.7	−22.2	3.0	−2.1	−1.6	−35.6
08b	−12.3	−19.7	2.7	−2.9	−1.7	−34.0
04a	−13.7	−20.5	0.6	−3.8	−1.0	−38.5
97f	−14.3	−22.4	2.4	3.8	−1.2	−31.8

In Table 1 we show the potential energies U_Λ for a zero-momentum Λ and their partial-wave contributions at normal density ρ_0 (k_F=1.35 fm^{-1}). Hereafter, a statistical factor $(2T + 1)(2J + 1)$ is included in each $^{2S+1}L_J$ contribution. The ^3P contribution means the sum of ^3P_J ($J = 0, 1, 2$) contributions, and the D contribution does the sum of $^1D_2$ and ^3D_J contributions. The obtained results for ESC08a/b are compared with those for ESC04a [1] and NSC97f [2]. In the Tables, ESC08a/b, ESC04a and NSC97f are denoted as 08a/b, 04a and 97f, respectively. The S-state contributions in ESC08a (ESC08b) are found to be comparable to (slightly less attractive than) those in ESC04a and NSC97f. The P-state contributions in ESC08a/b are very similar to each other, and they are less attractive than those in ESC04a. On the other hand, those in NSC97f are repulsive contrastively to the ESC models.

The spin-dependent features of the ΛN G-matrix interactions are very important, because they are tested by

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indications from hypernuclear data. The contributions to U_Λ from S-state spin-spin components can be seen qualitatively in values of $U_{\sigma\sigma} = (U_\Lambda(^3S_1) - 3U_\Lambda(^1S_0))/12$. Various analyses suggest that the reasonable value of $U_{\sigma\sigma}(\rho_0)$ is between those of NSC97e and NSC97f, which are 1.05 and 1.70 MeV, respectively [2]. The obtained values for ESC08a and ESC08b are 1.32 and 1.44 MeV, respectively: It turns out that the S-state spin-spin components of ESC08a/b are of nice strengths.

Table 2. $U_\Sigma(\rho_0)$ and partial wave contributions.

	T	$^1S_0$	$^3S_1$	$^1P_1$	^3P	D	U_Σ
08a	1/2	11.3	−23.9	2.3	−6.0	−0.7	
	3/2	−11.7	44.8	−7.2	4.9	−0.2	+13.4
08b	1/2	10.3	−26.2	2.5	−7.4	−0.8	
	3/2	−10.6	52.7	−6.2	6.3	−0.1	+20.3
04a	1/2	11.6	−26.9	2.4	−5.7	−0.8	
	3/2	−11.3	2.6	−6.8	−1.5	−0.2	−36.5
97f	1/2	14.9	−8.3	2.1	−1.6	−0.5	
	3/2	−12.4	−4.1	−4.1	1.1	−0.1	−12.9

In Table 2 we show the potential energies $U_\Sigma(\rho_0)$ and the partial wave contributions. It should be noted here that the strongly repulsive values of U_Σ can be obtained for ESC08a/b. Contrastively, the U_Σ values for all NSC and ESC models are attractive [1] [2]. In the case of the quark-cluster models, the repulsive nature of U_Σ is due to the existence of almost Pauli-forbidden states in $T = 1/2$ $^1S_0$ and $T = 3/2$ $^3S_1$ states, where the latter contribution with the large statistical weight is distinctly important for the repulsive value of U_Σ. On the other hand, in the conventional Nijmegen soft-core models (NSC, ESC), the repulsive cores are given by pomeron and ω meson exchanges etc., which are of similar strengths in all channels. In the case of ESC08 modeling, the above excellent feature of the quark-cluster model is taken into account phenomenologically by strengthening the pomeron coupling in these states. Then, it should be noted that the contributions in the $T = 3/2$ $^3S_1$ states for ESC08a/b are remarkably repulsive contrastively those for ESC04a and NSC97f, as found in Table 2. Experimentally, the repulsive Σ-nucleus potentials are suggested in the observed (π^-, K^-)spectra [4]. It is quite interesting that the repulsive values of U_Σ can be realized under the specific modeling for the core part of the *YN* interaction.

In Table 3 we show the potential energies $U_\Xi(\rho_0)$ and the partial wave contributions for ESC08a/b and ESC04d, where the U_Ξ values are found to be substantially attractive in the cases of ESC08a/b and ESC04d. However, the partial-wave contributions to U_Ξ are distinctly different from each other: In the case of ESC08a/b (ESC04d), the attractive contributions to U_Ξ are dominated by those in the $T = 1$ $(T = 0)$ $^3S_1$ state. As discussed in Ref.[1], the strong $T = 0$ $^3S_1$-state attraction in ESC04d is because the contributions of vector and axial-vector meson exchanges are strongly cancelled in this channel. The strong $T = 1$ $^3S_1$-state attractions in ESC08a/b are caused by the strong ΞN-$\Lambda\Sigma$-$\Sigma\Sigma$ coupling interactions, where these strengths come from the pair terms dominantly. The ΞN-$\Lambda\Sigma$-$\Sigma\Sigma$ triplet in the $T = 1$ state belongs to the baryon-baryon decuplet-state $\{10^*\}$ together with the $T = 0$ np and $T = 1/2$ ΛN-ΣN pair. It is interesting that the ΞN-$\Lambda\Sigma$-$\Sigma\Sigma$ coupling tensor interactions in ESC08a/b work similarly with the np and ΛN-ΣN tensor interactions. If these coupling interactions are switched off, the $T = 1$ $^3S_1$-state contributions become repulsive. The calculated values of conversion widths $\Gamma_\Xi(\rho_0)$ are also given in Table 3, the contributions of which come dominantly from the $\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ coupling interactions in $T = 0$ $^1S_0$ states. Here, it is found that the values of Γ_Ξ for ESC08a/b are substantially smaller than that for ESC04d.

Table 3. $U_\Xi(\rho_0)$ and partial wave contributions. Conversion width Γ_Ξ.

	T	$^1S_0$	$^3S_1$	$^1P_1$	^3P	U_Ξ	Γ_Ξ
08a	0	6.0	−1.0	−0.3	−2.1		
	1	8.5	−28.0	0.6	−3.8	−20.2	5.8
08a’	0	5.6	−1.1	−0.3	−2.2		
	1	8.4	−21.5	0.6	−3.9	−14.5	7.0
08b	0	2.4	1.9	−0.6	−2.0		
	1	9.1	−37.8	0.6	−5.4	−31.8	1.2
04d	0	6.4	−19.6	1.1	−2.2		
	1	6.4	−5.0	−1.0	−4.8	−18.7	11.3

3 Some Ξ-bound systems

Though there is almost no experimental information for ΞN interactions, the BNL-E885 experiment [5] indicates that a Ξ single particle potential in ^{11}B core is given by the attractive Wood-Saxon potential with the depth ~ -14 MeV (called WS14). It is found that the values of $U_\Xi(\rho_0)$ for ESC08a/b in Table 3 are rather more attractive than this WS depth, though the latter should not be compared strictly with the former quantities. Here, we modify ESC08a so as to be comparable to WS14 by weakening artificially the ΞN-$\Lambda\Sigma$-$\Sigma\Sigma$ coupling interaction in the $T = 1$ $^3S_1$ state. This version is denoted as ESC04a’ in Table 3. The U_Ξ value −14.5 MeV for ESC08a’ is noted to be very similar to the depth of WS14. In the present calculations, the results for ESC08a’ are compared with those for ESC04d. Then, also ESC04d is modified so as to be consistent with WS14 according to the way given in Ref. [6].

For applications to finite Ξ systems, the obtained complex ΞN G-matrix interactions are represented as k_F-dependent local potentials

$$G^{(\pm)}_{TS}(r, k_F) = \sum_{i=1}^{3} (a_i + b_i k_F + c_i k_F^2)\, \exp(-r^2/\beta_i^2)\,, \quad (1)$$

where k_F is a Fermi momentum of nuclear matter. The suffices (+) and (−) specify even and odd, respectively. The interaction parameters (a_i, b_i, c_i and β_i) of the G-matrix interaction for ESC08a’ are tabulated in Table 4. When this G-matrix interaction is applied to finite Ξ systems, the k_F

Table 4. The G-matrix interaction for ESC08a' represented as $G(k_F;r) = \sum_i (a_i + b_i k_F + c_i k_F^2) \exp -(r/\beta_i)^2$.

	β_i	0.50	0.90	2.00
$T = 0$				
	a	0.0	−602.4−407.3i	−2.623
^1E	b	0.0	1049.+554.9i	0.0
	c	0.0	−353.1−239.0i	0.0
	a	979.6	−258.8	2.316
^3E	b	−403.1	143.2	−3.130
	c	121.4	−38.44	1.130
	a	1421.	11.40	−6.242
^1O	b	−463.3	39.38	−.05188
	c	193.5	−10.55	−.03506
	a	0.0	−1025.−339.8i	−2.102
^3O	b	0.0	1431.+536.0i	0.0
	c	0.0	−543.2−214.1i	0.0
$T = 1$				
	a	107.5	−21.49	1.944
^1E	b	11.18	74.69	−2.846
	c	47.40	−22.49	.9266
	a	−975.0	40.25	−2.372
^3E	b	1910.	−250.5	.9788
	c	−725.8	105.1	−.4299
	a	1455.	−151.0	1.351
^1O	b	−1900.	205.8	−1.054
	c	731.8	−63.80	.2674
	a	889.9	−118.8	−1.679
^3O	b	498.1	5.448	−.1027
	c	−235.1	5.584	−.0013

parameters should be taken so as to agree with their adequate values in respective systems. It is difficult, however, to perform this procedure strictly in the present case, because of no experimental information on Ξ hypernuclei. It is inevitable here to choose the k_F values rather arbitrarily in a reasonable region (0.8 ∼ 1.2 fm^{-1} in light p-shell systems).

In Ref. [6], the ${}^{7}_{\Xi^-}$H and ${}^{10}_{\Xi^-}$Li systems were studied with use of the $\alpha nn\Xi^-$ and $\alpha\alpha n\Xi^-$ four-body cluster models, which can be produced by the (K^-, K^+) reaction on ^{7}Li and ^{10}B targets, respectively. In this previous work, the ΞN G-matrix interactions were derived from ESC04d and the Nijmegen hard-core model D, from which the Ξ-α interactions were obtained by the folding procedures. In the same framework, the calculations are performed with the ΞN G-matrix interaction for ESC08a', and the results are compared with those for ESC04d. In calculations, it is inadequate to use the G-matrix interaction for Ξn parts in the four-body models, because the degrees of freedom are fully taken into account for n and Ξ: We use a simple single-channel Ξn interaction, as explained in Ref. [6].

Table 5 gives the calculated values of the Ξ^- binding energies B_{Ξ^-} and the conversion widths Γ_{Ξ^-} for an $\alpha\Xi^-$ ground state, where the same value 0.9 fm^{-1} of k_F is chosen in both cases of ESC08a' and ESC04d. $\alpha\Xi^-$ Coulomb interactions are taken into account. Here, we obtain the similar values of $B_{\Xi^-}(\alpha\Xi^-)$ for ESC08a' and ESC04d. This means that the spin- and isospin-averaged $\alpha\Xi$ interactions

Table 5. Calculated values of B_{Ξ^-} and Γ_{Ξ^-} for an $\alpha\Xi^-$ system. The parameter k_F is taken as 0.9 fm^{-1}. Coulomb interactions are included.

		04d	08a'
$\alpha\Xi^-$	B_{Ξ^-}	1.36	1.33
	Γ_{Ξ^-}	2.64	1.54

obtained from ESC08a' and ESC04d are similar to each other in spite of remarkable difference of their spin- and isospin-dependences. Another important point is that the obtained values of Γ_Ξ for ESC08a' are rather smaller than those for ESC04d.

Table 6. Calculated values of B_{Ξ^-} and Γ_{Ξ^-} for 1^- and 2^- states of ${}^{12}_{\Xi^-}$Be ($\alpha\alpha t\Xi^-$) in MeV. The values in parentheses are calculated without Coulomb interactions.

		04d	08a'
	k_F	1.055	1.145
1^-	B_{Ξ^-}	5.0	3.9
		(2.2)	(2.2)
	Γ_{Ξ^-}	4.6	2.3
2^-	B_{Ξ^-}	6.1	4.6
	Γ_{Ξ^-}	4.8	2.5

Table 6 gives the values of B_{Ξ^-} and Γ_{Ξ^-} for 1^- and 2^- states of ${}^{12}_{\Xi^-}$Be calculated with the $\alpha\alpha t\Xi^-$ cluster model. Here, the k_F values for ESC08a' and ESC04d are chosen so as to reproduce the B_Ξ value of 2.2 MeV without the Coulomb interaction. This value is close to the s-state Ξ binding energy obtained from WS14. Thus, both the G-matrix interactions derived from ESC08a' and ESC04d are found to be adjusted so as to be consistent with the Ξ-nucleus attractions indicated in the E885 experiment.

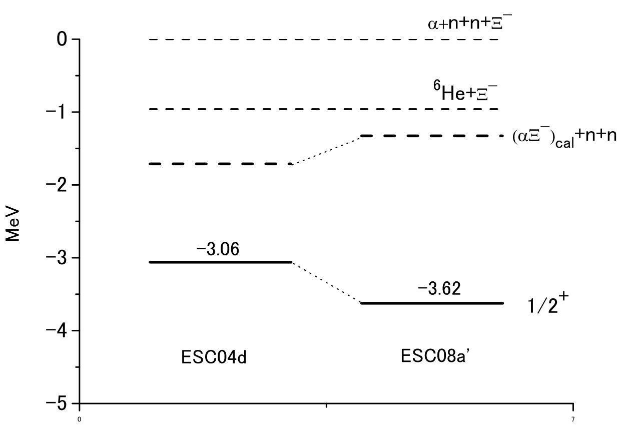

Fig. 1. Calculated energies of the $1/2^+$ state in ${}^{7}_{\Xi^-}$H are shown by solid lines. The dashed lines show the $(\alpha\Xi^-)_{cal} + n + n$ threshold energies.

Now, let us show the result for the ${}^{7}_{\Xi^-}$H. The core nucleus ^{6}He is in a bound state composed of α and weakly-bound two neutrons. In Ref. [6], the $\alpha nn\Xi$ system was demonstrated to be in a bound state when the $\alpha\Xi$ folding interaction was attractive enough to make an $\alpha\Xi$ bound state. Though the $\alpha\Xi$ interactions derived from ESC04d and ESC08a' are similar to each other, their $\Xi^- n$ parts are very different: That for ESC08a' (ESC04d) and are substantially (very weakly) attractive. The calculated Ξ^- energies in ${}^{7}_{\Xi^-}$H for ESC04d and ESC08a' are given by solid lines in Fig.1. The dashed lines show the $(\alpha\Xi^-)_{cal} + n + n$ threshold energies, $(\alpha\Xi^-)_{cal}$ being the calculated value of the $\alpha\Xi^-$ binding energy. The Ξ^- state given by ESC08a' is found to be more bound than that by ESC04d. This is an example that the strong ΞN attraction in the $T = 1\ {}^3S_1$ state works favorably to Ξ^- states produced by (K^-, K^+) reactions on available targets. The corresponding result for ${}^{10}_{\Xi^-}$Li is given in Fig.2. Here, the difference between the results for ESC04d and ESC08a' is found to be reduced in comparison with the ${}^{7}_{\Xi^-}$H case. The reason is understood as follows: The main difference of the two interaction models is in their $\Xi^- n$ parts. There are two $\Xi^- n$ bonds in ${}^{7}_{\Xi^-}$H, but only one bond in ${}^{10}_{\Xi^-}$Li.

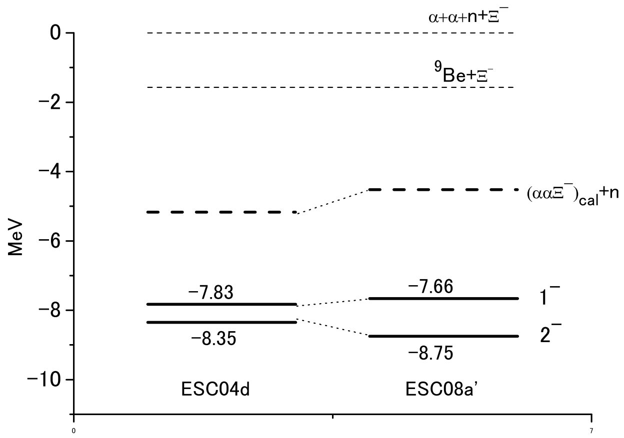

Fig. 2. Calculated energies of the 2^- and 1^- states in ${}^{10}_{\Xi^-}$Li are shown by solid lines. The dashed lines show the $(\alpha\alpha\Xi^-)_{cal} + n$ threshold energies.

It is very important that the $T = 1$ ΞN attractions are strong in the case of ESC08a/b. In the present experimental situation, the most promising production of Ξ^- hypernuclei are by (K^-, K^+) reactions. Then, produced Ξ^- systems have to be in neutron-excess, because of $\Delta T_z = 1$ transfers on available nuclear targets. For such systems, the $T = 1$ ΞN attractions work favorably. On the basis of ESC08a/b, it is expected that there exist various light Ξ^- bound systems other than ${}^{7}_{\Xi^-}$H ($\alpha nn\Xi^-$) and ${}^{10}_{\Xi^-}$Li ($\alpha\alpha n\Xi^-$). For instance, a few-body bound systems such as $nn\Xi^-$, $pn\Xi^-$, $pnn\Xi^-$, $\alpha n\Xi^-$ and $\alpha tn\Xi^-$ might be produced by (K^-, K^+) reactions on ^{3}H, ^{3}He, ^{4}He, ^{6}Li and ^{9}Be targets, respectively.

References

1. Th.A. Rijken and Y. Yamamoto, Phys. Rev. **C73** (2006) 044008.
2. Th.A. Rijken, V.G.J. Stoks, and Y. Yamamoto, Phys. Rev. **C59** (1999) 21.
3. Th.A. Rijken, M.M. Nagels, and Y. Yamamoto, to be published.
4. H. Noumi et. al., Phys. Rev. Lett. **89** (2002) 072301.
5. P. Khaustov *et al.*, Phys. Rev. **C61** (2000) 054603.
6. E. Hiyama, Y. Yamamoto, T. Motoba, Th. A. Rijken and M. Kamimura Phys. Rev. **C78** (2008) 054316