

Constraints on the Λ -neutron interaction from charge-symmetry breaking of $A = 4$ hypernuclei

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We include the leading charge symmetry breaking contributions into the hyperon-nucleon interactions derived within chiral effective field theory up to next-to-leading order. Two low energy constants are determined using the experimentally known differences of Λ separation energies of ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$. This allows one to predict the Λ -neutron scattering lengths for the first time based on data. Various sources of uncertainty are discussed.

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1. Introduction

To understand the interior of neutron stars a thorough knowledge on the equation of state (EOS) of nuclear matter is the prerequisite. This includes to also pin down the possible contribution of hyperons to nuclear, especially neutron, matter. Simply including hyperon degrees of freedom leads to a much too soft EOS that does not support the existence of neutron stars with mass about or larger as two solar masses [1–4]. This is generally referred to as hyperon puzzle. For a microscopic understanding of nuclear matter, it is therefore of utmost importance to study the properties of hyperon-nucleon (YN) interactions. Such YN interactions should then not only describe all available YN scattering data and hypernuclei but also lead to a contribution of hyperons to nuclear matter that is consistent with the observed neutron star masses [5–9] and radii [10–13].

Obviously, the most relevant interaction to be studied in this context is the one of Λ and neutron (Λn). Unfortunately, there is no scattering data for elastic Λn scattering so that the interaction is usually determined by Λ proton (Λp) data assuming isospin symmetry. Very early on, it was observed that isospin symmetry is significantly violated for these systems as can be seen from the charge symmetry breaking (CSB) Λ separation energy differences of $A = 4$ hypernuclei. Depending on the state considered, it can be as large as 250 keV which is at least four times larger than the strong interaction contribution to the CSB of $A = 3$ ordinary nuclei [14]. One important contribution to this CSB has been related to Σ^0 - Λ mixing. This effectively results in a one-pion exchange contribution to the ΛN interaction which is CSB [15]. The contribution is part of, e.g., the Nijmegen SC97 interactions [16] but cannot explain the CSB of $A = 4$ hypernuclei within this model [17]. Gal and Gazda [18–20] recently studied the same contribution based on the leading order (LO) chiral YN interaction [21]. While they found that for specific choices of the cutoff the CSB is correctly reproduced, they also observed a considerable dependence on the cutoff.

Besides the phenomenological importance, the CSB is also conceptually interesting since it is linked to the Λ - Σ conversion of YN interactions. One important contribution to the CSB of $A = 4$ hypernuclei is related to the mass difference of Σ particles. The strong Λ - Σ conversion process of YN interactions leads to a small, unfortunately non-observable, Σ component of hypernuclear wave functions. Model calculations show that this mass differences leads to a visible contribution to the CSB of the kinetic energy which is essentially proportional to the Σ probability for the hypernucleus [17].

From the perspective of chiral effective field theory, there are two momentum independent, CSB contact interaction at the same order as the CSB one-pion exchange. So far, these contact interactions have always been neglected. In Ref. [22], we introduce these contact interactions for the first time and determined the values of the related low energy constants (LECs) using the experimentally known values for the splitting of the separation energies of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ in the 0^+ and 1^+ states. This completely determines the leading CSB interaction and allows one to predict Λn and Λp singlet and triplet scattering lengths based on data. In this contribution, we summarize these results. We start with a short discussion on chiral YN interactions in Sec. 2 focusing on our approach to estimate higher order contributions, especially three-baryon forces (3BFs). In Sec. 3, we discuss the most important CSB contributions to YN interactions based on chiral effective field theory (EFT). The determination of the two CSB LECs and predictions for the ΛN scattering lengths are shown in Sec. 4. Finally, we conclude and give an outlook in Sec. 5.

interaction	$E_{\Lambda}({}^3_{\Lambda}\text{H})$	$E_{\Lambda}({}^4_{\Lambda}\text{He})$		$E_{\Lambda}({}^4_{\Lambda}\text{H})$	
		$J^{\pi} = 0^{+}$	$J^{\pi} = 1^{+}$	$J^{\pi} = 0^{+}$	$J^{\pi} = 1^{+}$
NLO13(500)	0.13	1.71	0.80	1.66	0.78
NLO13(550)	0.09	1.51	0.59	1.45	0.57
NLO13(600)	0.09	1.48	0.59	1.43	0.56
NLO13(650)	0.08	1.50	0.62	1.45	0.60
NLO19(500)	0.10	1.65	1.23	1.63	1.23
NLO19(550)	0.09	1.55	1.25	1.53	1.24
NLO19(600)	0.10	1.47	1.06	1.44	1.05
NLO19(650)	0.09	1.54	0.92	1.50	0.91
Expt.	0.13(5) [27]	2.39(3)[28]	0.98(3)[28]	2.16(8)[29]	1.07(8) [29]

Table 1: ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ separation energies for NLO13 and NLO19 for various cutoffs. No explicit CSB is included in the YN potentials. Energies are in MeV.

2. Chiral YN interactions and estimates for 3BF contributions

Our study is based on chiral YN interactions at next-to-leading order (NLO) [23, 24]. Up to this order, there are contributions of one- and two pseudoscalar (Goldstone) boson exchanges and more than 20 different short range contact interaction. Coupling constants of Goldstone bosons to baryons can be related by using $SU(3)$ flavor symmetry. On the other hand, $SU(3)$ symmetry is broken by using physical masses for the octet mesons. Since there are only 35 data available (new data has been obtained only recently [25, 26]), a unique determination of all low energy constants is not possible. In fact, it turned out that it is even possible to define two realizations of the chiral interaction at NLO that are almost phase shift equivalent. We refer to these version as NLO13 [23] and NLO19 [24]. These chiral YN interactions need to be regularized. For both NLO13 and NLO19, a cutoff between 500 MeV and 650 MeV is used for this regularization. Within this range of cutoffs, we obtained the best description of the available YN data.

As has been discussed in Ref. [24], both version differ mainly by their strength of the Λ - Σ transition potential thereby keeping the transition cross sections very similar to each other. Although, both interactions give almost identical results for the YN system, the predictions for systems with $A > 2$ are different. Such differences can be traced back to higher order contributions, i.e. three-baryon force (3BF) contributions, which first appear at next-to-next-to-leading order ($N^2\text{LO}$) [30].

In Table 1, this is shown for $A = 3$ and $A = 4$ hypernuclei. For calculating these systems, we also have to employ NN interactions. Since we will be discussing Λ separation energies, i.e. the differences of the binding energy of the core and the hypernucleus, the results will only mildly dependent on the NN interaction used [17, 24]. In this work, we therefore only employed one NN interaction: the chiral SMS regulated interaction at order $N^4\text{LO}+$ with a cutoff of 450 MeV [31].

It is reassuring that the variation of Λ separation energies is only about 40 keV for ${}^3_{\Lambda}\text{H}$. This is of the order of the experimental uncertainty and justifies to adjust the relative strength of the 1S_0 and 3S_1 YN interactions such that ${}^3_{\Lambda}\text{H}$ is described in agreement with experiment. In absence of YN

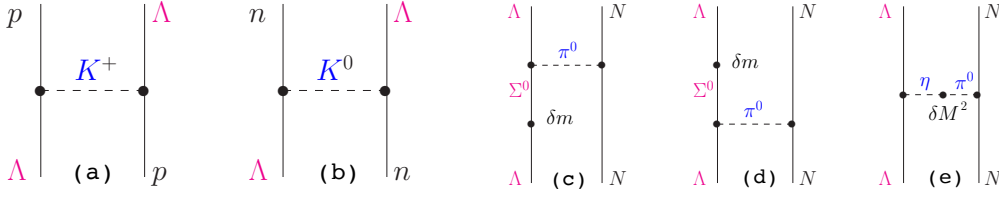


Figure 1: CSB contributions involving kaon and pion exchange.

data determining the spin dependence, this essentially fixes the ΛN scattering lengths. Note that this approach has only been done for the 600 MeV cutoff. For the other cutoffs, the interaction has been fitted to the scattering length obtain for 600 MeV. Therefore, the small variation of the energies are still a measure for N²LO, especially 3BF contributions to ${}^3_\Lambda\text{H}$. Due to the small separation energy of this system, such contributions seem to be suppressed.

This is not case for $A = 4$ hypernuclei anymore. For the 0^+ state, the variation of the Λ separation energy is about 240 keV. For the 1^+ state, it is even as large as 650 keV. Clearly, eventually, 3BFs need to be added to improve the predictions for these hypernuclei. However, for a first study of CSB in $A = 4$ hypernuclei, the description is still sufficiently realistic to allow for a sensible estimate. It will be important later on to perform the calculations using both versions of the NLO interactions and all cutoffs to ensure that higher order contributions do not affect the results significantly.

The results shown in Table 1 do not include CSB of the YN interaction. But they already include CSB due to the mass differences of Σ^+ , Σ^0 , Σ^- [32]. Also the contribution of the proton-proton Coulomb interaction changes compared to the one of the core nucleus. The inclusion of these two effects explains the small CSB of the separation energies shown in the table.

3. Leading contributions to CSB YN interactions

The implementation of CSB in chiral EFT has already been discussed for the nucleon-nucleon (NN) system in Refs. [33–35]. Thereby, the relevant expansion parameter is $\epsilon M_\pi^2/\Lambda^2 \sim 10^{-2}$, where $\epsilon \equiv \frac{m_d - m_u}{m_d + m_u} \sim 0.3$ is a ratio of quark masses and $\Lambda \sim M_\rho$.

The formally leading contributions at order $n = 1$ ($L\emptyset$) are due to the Coulomb interactions and due to mass differences between the exchanged pseudo-Goldstone bosons, i.e. $M_{\pi^\pm} - M_{\pi^0}$ and $M_{K^\pm} - M_{K^0}$. For the ΛN system, only the contributions due to $M_{K^\pm} - M_{K^0}$ contribute (see Fig. 1 (a) and (b)). Because the kaon masses are rather large compared to their mass difference, it turns out that this effect is actually very small. It is included in our calculations, but is quantitatively not important. The more important contributions are therefore formally subleading of order $n = 2$ ($NL\emptyset$). This includes the isospin violation in the pion-baryon coupling constant due to $\Sigma^0 - \Lambda$ mixing as well as from $\pi^0 - \eta$ mixing leading to a CSB one-pion exchange contribution to the ΛN interaction as depicted in Fig. 1 (c) to (e). The former mechanism was already introduced in Ref. [15] and is the basis of most studies of CSB in the YN system. Using the PDG mass values [32],

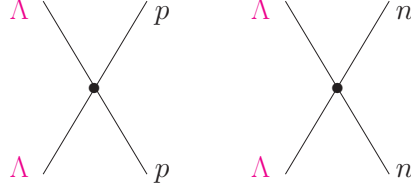


Figure 2: CSB contact interactions contributing to ΛN interactions.

one obtains for the CSB effective ΛN coupling constant

$$f_{\Lambda\Lambda\pi} = \left[-2 \frac{\langle \Sigma^0 | \delta m | \Lambda \rangle}{m_{\Sigma^0} - m_{\Lambda}} + \frac{\langle \pi^0 | \delta M^2 | \eta \rangle}{M_{\eta}^2 - M_{\pi^0}^2} \right] f_{\Lambda\Sigma\pi} \approx (-0.0297 - 0.0106) f_{\Lambda\Sigma\pi}. \quad (1)$$

New in our work is that we take into account the additional contributions from short range forces (arising from, e.g., $\rho^0 - \omega$ mixing) which, in chiral EFT, are represented by contact terms involving CSB LECs (see Fig. 2). There are two such contact forces, one for singlet and one for triplet ΛN , which are also required to properly renormalize the one-pion exchange contribution. In the following, we will determine these LECs using the CSB splitting of the separation energies of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ for the 0^+ and 1^+ state.

4. Results

In order to predict the CSB for the ΛN scattering lengths, we first need to determine the CSB LECs for the singlet (C_s^{CSB}) and triplet (C_t^{CSB}) states. To this aim, we use the difference of the Λ separation energies

$$\begin{aligned} \Delta E(0^+) &= E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{He}) - E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{H}), \\ \Delta E(1^+) &= E_{\Lambda}^{1^+}({}^4_{\Lambda}\text{He}) - E_{\Lambda}^{1^+}({}^4_{\Lambda}\text{H}). \end{aligned} \quad (2)$$

Here, we only discuss results based on the central values of the present experimental situation, i.e. on the recent measurements of $E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{H})$ in Mainz [29] and the one of $E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{He}) - E_{\Lambda}^{1^+}({}^4_{\Lambda}\text{He})$ at J-PARC [28], the old emulsion result of $E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{He})$ [27] and $E_{\Lambda}^{0^+}({}^4_{\Lambda}\text{H}) - E_{\Lambda}^{1^+}({}^4_{\Lambda}\text{H})$ from [36]. We refer to this scenario as CSB1 leading to $\Delta E(0^+) = 233 \pm 92$ keV and $\Delta E(1^+) = -83 \pm 94$ keV. Note that we discuss in Ref. [22] also older experimental values for these splittings.

The fitting is based on Faddeev-Yakubovsky calculations in momentum space using the isospin conserving YN interactions (see Table 1). We restricted all orbital angular momenta to $l \leq 4$ and the YN and NN pair angular momentum also to $j \leq 4$. Additionally, also the sum of the three orbital angular momenta required for our representation in Jacobi coordinates is restricted to 10. Thereby, only total isospin $T = 1/2$ is taken into account. This insures that the numerical uncertainty is better than 10 keV for the energies entering the Yakubovsky equations and 20 keV for expectation values of the energy. Interestingly, most of this uncertainty is due to the missing total isospin components with $T = 3/2$ and $T = 5/2$.

Based on the wave functions for ${}^4_{\Lambda}\text{He}$, we evaluated the individual contributions of the baryon mass differences in the kinetic energy, CSB one-pion exchange and the singlet and triplet CSB

Λ	NLO13		NLO19	
	C_s^{CSB}	C_t^{CSB}	C_s^{CSB}	C_t^{CSB}
500	4.691×10^{-3}	-9.294×10^{-4}	5.590×10^{-3}	-9.505×10^{-4}
550	6.724×10^{-3}	-8.625×10^{-4}	6.863×10^{-3}	-1.260×10^{-3}
600	9.960×10^{-3}	-9.870×10^{-4}	9.217×10^{-3}	-1.305×10^{-3}
650	1.500×10^{-2}	-1.142×10^{-3}	1.240×10^{-2}	-1.395×10^{-3}

Table 2: CSB contact terms used for the singlet (s) and triplet (t) ΛN interactions. The values of the LECs are in 10^4 GeV^{-2} .

interaction	$\langle T \rangle_{\text{CSB}}$	$\langle V_{YN} \rangle_{\text{CSB}}$	V_{NN}^{CSB}	$\Delta E_{\Lambda}^{\text{pert}}$	ΔE_{Λ}
NLO13(500)	44	200	16	261	265
NLO13(550)	46	191	20	257	261
NLO13(600)	44	187	20	252	256
NLO13(650)	38	189	18	245	249
NLO19(500)	14	224	5	243	249
NLO19(550)	14	226	7	247	252
NLO19(600)	22	204	12	238	243
NLO19(650)	26	207	12	245	250

Table 3: Perturbative estimate of the CSB of ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ separation energies $\Delta E_{\Lambda}^{\text{pert}}$ for the 0^+ state based on ${}^4_{\Lambda}\text{He}$ wave functions compared to the full result ΔE_{Λ} . The individual contributions due to the kinetic energy $\langle T \rangle_{\text{CSB}}$, the YN interaction $\langle V_{YN} \rangle_{\text{CSB}}$ and the contribution of the nuclear core $V_{NN}^{\text{CSB}} = \langle V_{NN} \rangle_{\text{CSB}} - E({}^3\text{He}) + E({}^3\text{H})$ are also shown. All energies are in keV.

contact interactions. This allows one to determine the corresponding LECs. The results are shown in Table 2 and are well in line with the power counting expectation of

$$C_{s/t}^{CSB} \propto \frac{m_d - m_u}{m_d + m_u} \left(\frac{M_{\pi}}{\Lambda} \right)^2 C_{s/t} \approx 6 \cdot 10^{-3} 10^4 \text{ GeV}^{-2}$$

where $C_{s/t}$ are the isospin conserving LO counter terms of the chiral ΛN interaction.

The fits are then used in full calculations for ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ and the CSB of the separation energies is also obtained from these full results. As can be seen in Table 3 for the 0^+ state, the perturbative and full results agree well. We also checked that this is the case for the 1^+ state. Additionally, the table shows the perturbatively estimated contributions of the kinetic energy, the YN interaction and the change in CSB of the nuclear interaction compared to the nuclear core (mostly due to the change of the Coulomb interaction and the contribution of the proton-neutron mass difference due to the compression of the core in the hypernucleus [37]). It can also be seen that the major part of the CSB is due to the YN interaction. For the 0^+ state, also the kinetic energy contribution due to the Σ^+ and Σ^- mass difference is visible. This part is strongly related to the probability to find a Σ in ${}^4_{\Lambda}\text{He}$ [17]. It is therefore not surprising that its size is different for NLO13 and NLO19. This also shows explicitly that the individual contributions to CSB are not observable but depend on the realization of the YN interaction.

	$a_s^{\Lambda p}$	$a_t^{\Lambda p}$	$a_s^{\Lambda n}$	$a_t^{\Lambda n}$	$\chi^2(\Lambda p)$	$\chi^2(\Sigma N)$	$\chi^2(\text{total})$
NLO13(500)	-2.604	-1.647	-3.267	-1.561	4.47	12.13	16.60
NLO13(550)	-2.586	-1.551	-3.291	-1.469	3.46	12.03	15.49
NLO13(600)	-2.588	-1.573	-3.291	-1.487	3.43	12.38	15.81
NLO13(650)	-2.592	-1.538	-3.271	-1.452	3.70	12.57	16.27
NLO19(500)	-2.649	-1.580	-3.202	-1.467	3.51	14.69	18.20
NLO19(550)	-2.640	-1.524	-3.205	-1.407	3.23	14.19	17.42
NLO19(600)	-2.632	-1.473	-3.227	-1.362	3.45	12.68	16.13
NLO19(650)	-2.620	-1.464	-3.225	-1.365	3.28	12.76	16.04

Table 4: Singlet ($a_s^{\Lambda p/\Lambda n}$) and triplet ($a_t^{\Lambda p/\Lambda n}$) S -wave scattering lengths for Λp and Λn scattering in fm^{-1} . χ^2 values for the comparison to the available YN data are also shown.

Finally, we used the so determined CSB YN interactions to predict the scattering lengths for ΛN scattering. For the CSB scenario used here, it turns out that the CSB is small for the triplet and sizable for the singlet state. Interestingly, the dependence on the realization of the chiral interaction, NLO13 or NLO19, and on the cutoff are small. Based on the central values of the currently best experimental results for the CSB of $A = 4$ nuclei, we find that the singlet scattering lengths for Λp and Λn are -2.6 fm and -3.2 fm. This does not yet include the uncertainty due to the uncertainty of the experimental results for $A = 4$ hypernuclei. Interestingly, the χ^2 values with respect to the YN scattering data slightly decrease when CSB is used for the calculation compared to the isospin conserving case (see [24]). The stability of these predictions for the scattering lengths indicate that the missing higher order interactions do not affect this result very much. In view of upcoming improved data for $A = 4$ hypernuclei, an accurate determination of the Λn scattering length will therefore be possible.

5. Conclusions and outlook

In conclusion, we have shown that $A = 4$ hypernuclei can provide important additional constraints for the Λp and Λn systems and can be used to accurately determine the CSB of these interactions. For the first time based on data, we found that the Λn interaction becomes more attractive in the 1S_0 partial wave when CSB is taken into account. For the currently best experimental data for $A = 4$ hypernuclei, the magnitude of the singlet scattering length increases from -2.9 fm to -3.2 fm. In this scenario, the triplet scattering lengths is less affected by CSB. We note that we have studied other scenarios using older data in Ref. [22]. For these scenarios, the changes of the scattering lengths can be different. It is therefore of utmost importance that also the ^4He ground state energy and the $^4_\Lambda\text{H}$ excitation energy is remeasured in order to confirm the old data and in order to reduce the experimental uncertainty. The work reported here shows that such data will provide clear constraints on the CSB of the YN interaction.

But our calculations should also be further refined. First of all, chiral 3BFs [30] should be included and could be used to improve the description of $A = 4$ separation energies. With such improved interactions, the CSB of p -shell hypernuclei can be studied using the Jacobi no-core shell model [38, 39]. This could open a path towards other, independent confirmations of the CSB in

YN interactions. Further, the uncertainty of the experimental input should be taken into account to get a realistic estimate of the accuracy of our predictions.

Acknowledgments

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