Light Λ Hypernuclei Studied with Chiral Hyperon-Nucleon and Hyperon-Nucleon-Nucleon Forces

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A study of light Λ hypernuclei in chiral effective field theory is presented. For the first time, chiral ΛNN and ΣNN three-body forces are included consistently. The calculations are performed within the no-core shell model. Results for the separation energies of the hypernuclei ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He, and ${}^{7}_{\Lambda}$Li are given. It is found that the experimental values can be fairly well reproduced once hyperon-nucleon-nucleon three-body forces are taken into account.

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Introduction—Three-body forces (3BFs) have a long and varied history in nuclear physics [1]. Initially, they were introduced on a phenomenological basis, in order to explain the observed discrepancy between the measured binding energies of light nuclei such as the triton or ^{4}He and the predictions based on realistic nucleon-nucleon (NN) potentials. The concept of 3BFs changed radically in the early 1990s with the pivotal works of Weinberg [2,3]. He introduced a framework that allows one to construct NN and three-nucleon forces (3NFs) consistently, namely, chiral effective field theory (EFT), together with a pertinent power counting that establishes a hierarchy for the relative strength and importance of 3N (4N, …) forces in relation to that of the NN interaction. Performing few-nucleon calculations based on this scheme is by now standard [4–9].

The 3BFs included in early hypernuclear physics calculations were likewise of purely phenomenological nature [10–13]. However, unlike the present situation in the few-nucleon sector mentioned above, even now hyperon-nucleon-nucleon (YNN) forces are still considered on a phenomenological level in essentially all pertinent investigations. This concerns not only studies of ordinary hypernuclei [14,15], but, in particular, the discussion on the role that hyperons play for the size and stability of neutron stars [16–18]. Specifically, for the latter issue, YNN 3BFs are seen as one of the most promising solutions for the so-called hyperon puzzle, i.e., the quest to reconcile the appearance of Λ's (and possibly other hyperons) at densities realized in compact objects like neutron stars, causing a softening of the equation of state (EOS), with the empirical constraints on their mass-radius relation that can be explained only with a stiff EOS [19–22]. Given their key role for this topic, it is vitally important to put the YNN 3BFs on a more solid ground.

Indeed, the first derivation of 3BFs involving baryons with strangeness (Λ, Σ, Ξ), based on SU(3) chiral EFT, was given only a few years ago [23]. In addition, recently the ΛN-ΣN interaction has been established up to next-to-next-to-leading order (N^{2}LO) in the chiral expansion [24], i.e., the order at which the leading YNN force formally appears in the Weinberg counting. Thus, all ingredients for a consistent inclusion of hyperon-nucleon (YN) and YNN forces in calculations of Λ hypernuclei are available now. Fortunately, on the computational side, rigorous calculations with so-called *ab initio* methods have become feasible [14,25–27]. Specifically, those within the no-core shell model (NCSM) have reached a level that allows the computation of hypernuclei up to $A = 8$ [28] (or even up to $A = 13$ [25]) based on state-of-the-art YN and YNN potentials.

In this Letter, we present the first calculation of light Λ hypernuclei ($A = 3$–7) employing YN and YNN interactions, both derived from chiral EFT. The essential accomplishment of this Letter is a consistent treatment of the YN and YNN forces up to N^{2}LO in the chiral expansion. To the best of our knowledge, there is only one other calculation of hypernuclei ($A = 3$–5) with similar ambition, which includes consistently ΛN and

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ΛNN forces [29]. However, it is performed in pionless EFT at leading order (LO). A recent study of hypernuclei within nuclear lattice effective field theory is likewise restricted to LO ΛN forces [30] and similarly for hyperneutron matter [31]. There are already calculations that include the chiral YNN force together with chiral YN interactions [32,33]. However, those have only exploratory character because the strength of the 3BF, encoded in so-called low-energy constants (LECs), was fixed using dimensional arguments and not by considering actual separation energies. Moreover, these studies are restricted to the hypertriton. In the present Letter, we determine the strength of the 3BF by adjusting the LECs to the ${}^{4}_{\Lambda}\mathrm{H}/{}^{4}_{\Lambda}\mathrm{He}$ and ${}^{5}_{\Lambda}\mathrm{He}$ bound states. Thereby, we want to answer two important questions: (i) Can the spectrum of $A = 3$–7 hypernuclei be described by including 3BFs, and, if so, how well? (ii) Are the resulting 3BFs consistent with the size expected from chiral power counting?

No-core shell model—We apply the Jacobi NCSM (J-NCSM) for calculating the Λ separation energies of the $A = 3$–7 hypernuclei. A detailed description of the formalism and of the procedure to extract the separation energies can be found in Ref. [27]. In all calculations, contributions of the NN (YN) potentials up to a total angular momentum of $J = 6(5)$ are included, while for the 3N interaction all partial waves with total angular momentum $J_{3\mathrm{N}} \leq 9/2$ are taken into account. It has been checked that higher partial waves only contribute negligibly compared to the harmonic oscillator model space uncertainties. In order to speed up the convergence of the NCSM with respect to the model space, all the employed NN, 3N, and YN potentials are similarity renormalization group (SRG) evolved to a flow parameter of $\lambda = 1.88\ \mathrm{fm}^{-1}$; see [27] and references therein. The latter is commonly used in nuclear calculations, which, on the one hand, yields rather well-converged nuclear binding energies, and on the other hand, minimizes the possible contribution of SRG-induced 4N and higher-body forces [34]. Furthermore, in all the calculations, the SRG-induced YNN interaction with the total angular momentum $J_{\mathrm{YNN}} \leq 5/2$ is included. Based on the contributions of $J_{\mathrm{YNN}} \leq 1/2$, $3/2$, and $5/2$, the contribution from higher partial waves $J_{\mathrm{YNN}} \geq 7/2$ is estimated to be negligibly small and, therefore, is omitted from the calculations. With the proper inclusion of these SRG-induced three-body forces, the otherwise strong dependence of the Λ separation energies on the SRG flow parameter [25,27] is practically removed for the $A = 3$, 4 systems and remains insignificantly small for ${}^{5}_{\Lambda}\mathrm{He}$ [26,35]. All calculations in this Letter will be based on the semi-local momentum space regularized (SMS) NN potential $\mathrm{N}^4\mathrm{LO}^+$ [36] with a cutoff of $\Lambda = 550$ MeV and include a corresponding $\mathrm{N}^2\mathrm{LO}$ 3NF [35]. For the YN interaction, the SMS potential $\mathrm{N}^2\mathrm{LO}(550^b)$ from Ref. [24] (also with $\Lambda = 550$ MeV) is employed. In addition, for the first time, the full leading chiral YNN forces at $\mathrm{N}^2\mathrm{LO}$ are taken into account. First exploratory studies of the contributions of the chiral ΛNN forces to the separation energies have been performed for the $A = 3$ hypernucleus [32,33] and $A = 3$–5 systems [37] using a nonlocal regulator.

Structure of the three-baryon force—The general structure of the leading 3BFs within SU(3) chiral EFT has been worked out in detail in [23]. Like in the 3N case [4,38], there are contributions to the 3BF from two-meson exchanges, one-meson exchanges, and six-baryon contact terms. However, since for YNN the Pauli principle is less restrictive, the corresponding 3BFs have a much richer structure. For example, regarding the contact term, there is only one such contribution to the 3N force, but eight in the ΛNN-ΣNN system [23]. To be concrete, while the three-nucleon contact potential in its antisymmetrized form (using the antisymmetrizer $\mathcal{A}$) is given by [38]

$$V_{\mathrm{ct}}^{3\mathrm{N}} = \frac{1}{2} E \mathcal{A} \sum_{j\neq k} \vec{\tau}_j \cdot \vec{\tau}_k, \tag{1}$$

the corresponding expression for the ΛNN → ΛNN potential from the contact term is [23]

$$\begin{aligned} V_{\mathrm{ct}}^{\Lambda\mathrm{NN}} = {} & C_1'(\mathbb{1} - \vec{\sigma}_2 \cdot \vec{\sigma}_3)(3 + \vec{\tau}_2 \cdot \vec{\tau}_3) \\ & + C_2' \vec{\sigma}_1 \cdot (\vec{\sigma}_2 + \vec{\sigma}_3)(\mathbb{1} - \vec{\tau}_2 \cdot \vec{\tau}_3) \\ & + C_3'(3 + \vec{\sigma}_2 \cdot \vec{\sigma}_3)(\mathbb{1} - \vec{\tau}_2 \cdot \vec{\tau}_3). \end{aligned} \tag{2}$$

Here, the $\vec{\sigma}_i$ and $\vec{\tau}_i$ are the standard Pauli operators for the spin of the baryons and the isospin of the nucleons, and E and the C''s are LECs that parametrize the strength of the contact interactions. The situation is similar for the one-meson exchange 3BF. In fact, considering only the contribution from one-pion exchange alone, there is one term (LEC) for 3N, two terms (LECs) for ΛNN [23], and already six further terms with the ΛNN-ΣNN transition potential.

Since the experimental uncertainty of the ${}^{3}_{\Lambda}\mathrm{H}$ separation energy [39] is comparable to the expected contribution from the ΛNN 3BF [35,37], it is not practical to determine the pertinent LECs from the hypertriton. Therefore, as argued in Ref. [24], the only possible and viable way to fix the 3BFs is via studies of the ${}^{4}_{\Lambda}\mathrm{H}/{}^{4}_{\Lambda}\mathrm{He}$ and ${}^{5}_{\Lambda}\mathrm{He}$ systems. This strategy is followed here. Still, as should be clear from the discussion above, the number of LECs for the leading YNN 3BF exceeds by far the available experimental constraints from light hypernuclei. Even if we consider only the ΛNN 3BF we would have to deal with five LECs (three for the contact terms and two from the one-pion exchange 3BF) to be compared with only two LECs in the 3N case [38].

In the present Letter, we restrict ourselves to the pion-exchange contributions, in line with the SMS YN potential [24] where two-meson contributions involving the K and/or η were neglected (which is also consistent with large-N_C arguments [40,41]), and we exploit the mechanism of

TABLE I. Separation energies for $A = 3$–7 hypernuclei with angular momentum and parity J^π and isospin T in MeV, calculated without and with inclusion of YNN three-body forces. See text for details on the employed NN (YN) and 3N (YNN) potentials. The number in parentheses indicates the estimated extrapolation uncertainties.

${}^{A}_{\Lambda}Z(J^\pi, T)$	Without YNN	YNN (C_1', C_3')	YNN (C_1', C_2', C_3')	Experiment [39]
${}^{3}_{\Lambda}H(1/2^+, 0)$	0.121(4)	0.125(4)	0.155(3)	0.164(43)
${}^{4}_{\Lambda}He(0^+, 1/2)$	1.954(1)	2.027(3)	2.220(2)	2.258(55) (average)
				2.169(42) (${}^{4}_{\Lambda}H$)
				2.347(36) (${}^{4}_{\Lambda}H$)
${}^{4}_{\Lambda}He(1^+, 1/2)$	1.168(20)	1.010(11)	0.984(12)	1.011(72) (average)
				1.081(46) (${}^{4}_{\Lambda}H$)
				0.942(36) (${}^{4}_{\Lambda}He$)
${}^{5}_{\Lambda}He(1/2^+, 0)$	3.518(20)	3.152(21)	3.196(20)	3.102(30)
${}^{7}_{\Lambda}Li(1/2^+, 0)$	5.719(56)	5.444(57)	5.623(52)	5.619(60)
${}^{7}_{\Lambda}Li(3/2^+, 0)$	5.522(70)	5.042(65)	5.040(57)	4.927(60)
${}^{7}_{\Lambda}Li(5/2^+, 0)$	3.440(66)	3.205(65)	3.356(60)	3.568(60)

resonance saturation via decuplet baryons (Δ, Σ^*, Ξ^*) to estimate the strengths of chiral 3BFs [42–44]. Indeed, by involving decuplet baryons (B^*) the resulting two-pion exchange ΛNN and ΣNN 3BFs are completely fixed by the $\Delta \to N\pi$ decay width and SU(3) flavor symmetry. The number of independent LECs for the one-pion exchange 3BFs and the contact term is strongly reduced, namely, to two for the ΛNN – ΣNN 3BFs and to a single LEC for ΛNN. For example, the LECs of the ΛNN contact interaction in Eq. (2) can then be written in terms of a simple combination of the two LECs of the leading order $BB \to BB^*$ contact interaction H_1 and H_2 in SU(3) chiral EFT, see Refs. [42,43], and amount to

$$C_1' = C_3' = \frac{(H_1 + 3H_2)^2}{72\Delta}, \qquad C_2' = 0, \tag{3}$$

where Δ is the average mass splitting between the octet and decuplet baryons, $\Delta \approx 300$ MeV. The contact interaction for ΛNN-ΣNN and ΣNN involve other combinations of H_1 and H_2 [42,43].

Note that, by including decuplet baryons as degrees of freedom in chiral EFT, the pertinent parts of the two-pion exchange ΛNN and ΣNN 3BF are promoted to NLO as well as contributions that involve contact vertices. Therefore, we expect that using decuplet saturation is a good starting point and should allow one to achieve a reliable semiquantitative estimate for the effects of the ΛNN and ΣNN 3BFs.

Results—Results for the separation energies of the hypernuclei ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He, and ${}^{7}_{\Lambda}$Li without YNN force can be found in the second column of Table I. We include in parentheses the numerical uncertainty due to a necessary extrapolation in the model space size. Obviously, the separation energies based on the two-body interaction alone are already fairly close to the experimental values, cf. the last column. Since, at present, no charge-symmetry breaking (CSB) is included in the YN potential, we have employed the experimentally isospin-averaged separation energies of ${}^{4}_{\Lambda}$He/${}^{4}_{\Lambda}$H (0+, 1+) states in fitting. Our theoretical results should therefore be compared with the averaged separation energies shown. Because CSB can be included perturbatively, fitting to the average is equivalent to including CSB for the fit. The other states are isospin $T = 0$ so that CSB does not contribute.

In a first step, we add ΛNN and ΣNN 3BFs based purely on decuplet saturation. In this case, there are two independent LECs whose values are adjusted with the aim to reproduce the separation energies for the 0^+ and 1^+ states of ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He and ${}^{5}_{\Lambda}$He. However, this can be only partially achieved, see third column of Table I. While for the latter two cases (which turned out to be correlated with each other) the energies with YNN force agree nicely with the experimental values within their uncertainties, the result for the 0^+ state of ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He remains noticeably below the empirical information. Regarding the other two hypernuclei, not considered when adjusting the LECs of the 3BF, it turns out that the result for ${}^{3}_{\Lambda}$H remains practically unchanged, while the separation energy for ${}^{7}_{\Lambda}$Li is now smaller than the experimental value. Given that a perfect description of all states was not possible, we chose for the LECs of the YNN force $H_1 = -0.68F_\pi^{-2}$, $H_2 = 0.016F_\pi^{-2}$, where $F_\pi = 92.4$ MeV. These values minimized the deviation of the 0^+ state, led to an agreement for the 1^+ state and $A = 5$ within the estimated uncertainty, and are consistent with naturalness.

Given the fact that with the decuplet saturation approximation alone it is not possible to simultaneously describe the levels in the $A = 4$ system and the separation energy of ${}^{5}_{\Lambda}$He, in a second step, we go beyond that scenario. Specifically, we allow the LEC C_2' to be different from zero while keeping C_1' and C_3' the same as in the initial fit. Note that the C_2' term introduces a 3BF that depends explicitly on the spin of the Λ [30], cf. Eq. (2). The

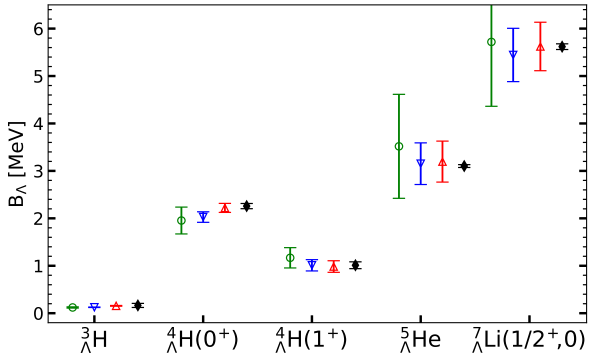

FIG. 1. Separation energies for $A = 3$–7 hypernuclei. Values at ${}^{4}_{\Lambda}$H show the average of ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He. Results are shown for the N^{2}LO YN potential without YNN force (green circles) and including YNN forces strictly (blue upsidedown triangles) or partially constrained (red triangles) by decuplet saturation. The bars indicate the estimated truncation error of the chiral expansion, see text. Experimental values (black diamonds) are taken from the chart of hypernuclides [39].

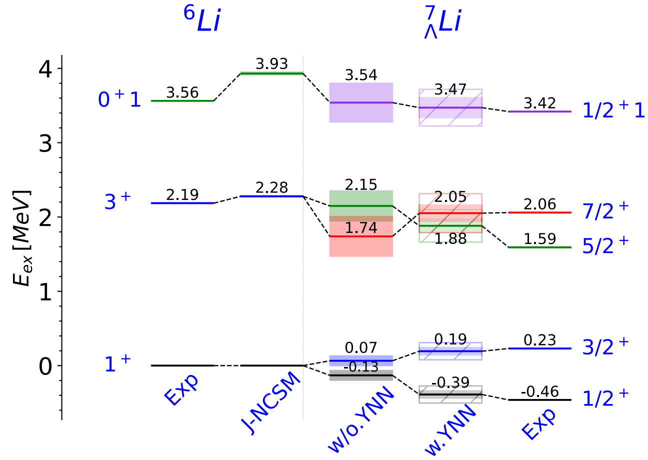

FIG. 2. Energy spectrum of ${}^{7}_{\Lambda}$Li, calculated without and with YNN three-body forces. Shaded areas show the extrapolated and chiral uncertainties at NLO and N^{2}LO for the case without and with chiral YNN forces, respectively. For the latter case, the hatched area represents uncertainties at NLO. Experimental values are taken from [48].

corresponding separation energies are presented in the fourth column of Table I, which have been achieved with a $C_2' = 1310$ GeV^{-5} of the expected size. Obviously, now all the ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He$(0^+, 1^+)$ and ${}^{5}_{\Lambda}$He separation energies can be well reproduced within the experimental uncertainty. Note that the spin-dependent YNN force induces a modest shift of the separation energy of ${}^{3}_{\Lambda}$H which brings it in better agreement with the experimental average of the Mainz group [39]. Also the ${}^{7}_{\Lambda}$Li separation energy is in remarkable agreement with experiment.

To provide an estimate for the theoretical uncertainty, we evaluated the truncation error of the chiral expansion based on the Bayesian approach [45,46]. We learn the convergence of the chiral expansion based on the results that are computed using the LO, NLO, and N^{2}LO YN interactions, see [35] for more details. At NLO and N^{2}LO we distinguish three cases, namely, without chiral YNN force and including YNN forces with strict or with partial constraints from decuplet saturation. The separation energies for $A = 3$–7 systems at N^{2}LO together with the theoretical uncertainties are displayed in Fig. 1. Expecting that the fits include the quantitatively most relevant parts of the YNN force, the chiral truncation errors are taken at N^{2}LO for the calculations including the chiral YNN forces, and at NLO otherwise. The experimental situation [39], is indicated by filled (black) diamonds. Obviously, the chiral truncation errors exceed the extrapolation uncertainties shown in the parentheses in Table I. Note that the shifts due to the YNN forces are well within the NLO uncertainties in Fig. 1. This indicates that the YNN contribution is in line with the power counting.

A detailed visualization of our predictions for the energy spectrum of the ${}^{7}_{\Lambda}$Li hypernucleus is provided in Fig. 2, with the excitation spectrum of the core nucleus ^{6}Li being shown on the right-hand side. As one can see, with the inclusion of the chiral 3NF, we reproduce the excitation energy of the $J^\pi = 3^+$ state of ^{6}Li fairly well. In order to further reduce the impact of the levels of the core nucleus, we focus our discussion on the relative positions of the energy levels of ${}^{7}_{\Lambda}$Li and plot them with respect to the ground-state centroid energy [47]. The bands indicate the estimated uncertainties from the extrapolation and from the chiral convergence study at NLO and N^{2}LO for the cases without and with YNN forces, respectively. For the latter case, we also show the truncation error at NLO (hatched area). Without chiral YNN forces, we can only quantitatively reproduce the ground-state splitting and the isospin $T = 1$ energy level. In particular, the level ordering of the $5/2^+$ and $7/2^+$ levels is opposite to the experiment. This behavior is also observed for NLO13 and NLO19 versions of the chiral YN potentials, which differs from our earlier results reported in [47] where the SRG-induced 3N and YNN forces were missing. As clearly seen in the fourth column of Fig. 2, the inclusion of the chiral YNN forces leads to significant improvement in the overall description of the ${}^{7}_{\Lambda}$Li spectrum. Specifically, the ground-state splitting as well as the $T = 1$ level are consistent with experiment within the estimated uncertainties, whereas the $5/2^+$ and $7/2^+$ levels are now correctly ordered. The shown results correspond to YNN forces with relaxed constraints from decuplet saturation, i.e., involving all C'_{1-3} LECs. The results for the strict decuplet scenario are in between the cases without YNN and the full calculation and have been omitted to improve the readability of the figure.

Summary—We have performed a study of light Λ hypernuclei within chiral EFT up to N^{2}LO where, for the first time, chiral ΛNN and ΣNN three-body forces are included consistently. The LECs of the YNN forces were determined by fitting to the ${}^4_\Lambda$H/${}^4_\Lambda$He and ${}^5_\Lambda$He separation energies, guided by constraints on their values from resonance saturation via decuplet baryons. Results for the hypernuclei ${}^3_\Lambda$H, ${}^4_\Lambda$H/${}^4_\Lambda$He, ${}^5_\Lambda$He, and ${}^7_\Lambda$Li could be achieved that agree well with experiments. Our calculations show that a consistent description of Λp scattering data and light hypernuclei is possible, when including 3BFs in line with the power counting of chiral EFT. One can certainly view that as confirmation of our present knowledge of the ΛN-ΣN interaction as represented by the chiral YN potentials. Nonetheless, one should not forget open issues like the so far basically unconstrained interaction in the higher partial waves of the ΛN system [24,49] and certain indications that the ΛN interaction could be possibly overall slightly weaker [50]. Finally, it is interesting to note that we observe a trend for repulsive effects of the required 3BFs with increasing A, which might be interpreted as support for one of the possible solutions of the hyperon puzzle in neutron stars.

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