Hyperon-nucleon interaction and light hypernuclei

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(Hoai Le, Ulf-G. Meißner, Andreas Nogga)



2 YN interaction in chiral effective field theory





Johann Haidenbauer Hyperon-nucleon interaction

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Hyperon physics - recent developments

- Role of hyperons in neutron stars ("hyperon puzzle") Neutron stars with masses ≥ 2M_☉ ⇒ stiff equation of state (EoS) With increasing density n → Λ ⇒ softening of the EoS ⇒ Conventional explanations of observed mass-radius relation fail
- New measurements of Λp cross sections by the CLAS Collaboration at JLab
 New extended measurements of ΣN observables in the E40 experiment at J-PARC differential cross sections for Σ⁺p, Σ⁻p
- Measurements of two-particle momentum correlation functions by the STAR, HADES, and ALICE Collaborations (Λρ, ΛΛ, Ξ⁻ρ, ...)
- HAL QCD: Lattice QCD simulations for *YN* interactions for quark masses close to the physical point ($M_{\pi} \approx 145 \text{ MeV}$)
- Progress in *ab initio* methods like no-core shell model (NCSM) microscopic calculations of hypernuclei up to A ≥ 10
- Nuclear lattice effective field theory including the Λ hyperon

BB interaction in chiral effective field theory

Baryon-baryon interaction in SU(3) χ EFT à la Weinberg (1990) Advantages:

Power counting

systematic improvement by going to higher order

 Possibility to derive two- and three-baryon forces and external current operators in a consistent way

• degrees of freedom: octet baryons (N, Λ , Σ , Ξ), pseudoscalar mesons (π , K, η)

- pseudoscalar-meson exchanges
- contact terms represent unresolved short-distance dynamics involve low-energy constants (LECs) that need to be fixed by a fit to data

 ΛN - ΣN interaction

LO: H. Polinder, J.H., U.-G. Meißner, NPA 779 (2006) 244
NLO13: J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24
NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91
SMS NLO, NNLO: J.H., U.-G. Meißner, A. Nogga, H.Le, EPJA 59 (2023) 63

(BB systems with strangeness S = -1 to -6)

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Extension of chiral EFT interaction up to NNLO

(Nucleon-nucleon forces in chiral EFT (E. Epelbaum))



N²LO: no new (additional) LECs in the two-body sector

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leading-order three-body forces (3BFs)
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NN interaction in chiral EFT

Semilocal momentum-space (SMS) regularized chiral NN potential



(Reinert, Krebs, Epelbaum, EPJA 54 (2018) 86) [up to N⁴LO (N⁴LO⁺) !!]

LO to NLO: drastic change in all partial waves

NLO to N²LO: changes mostly in *P*-waves and higher partial waves

Results for SMS chiral YN interactions



SMS YN potentials up to NLO, NNLO (with $\Lambda = 550$ MeV)

(J.H., U.-G. Meißner, A. Nogga, H. Le, EPJ A 59 (2023) 63) NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

quality of the fit – total χ^2 (36 data points): NLO19(600): 16.0 SMS NLO: 15.2 SMS NNLO: 15.6

cross sections dominated by S-waves (are already well described at NLO) \rightarrow (as expected) practically no change when going to NNLO

Results for SMS YN interactions



integrated cross sections at higher energies not included in the fitting process!

 $\Sigma^+ \rho \rightarrow \Sigma^+ \rho$ and $\Sigma^- \rho \rightarrow \Sigma^- \rho$ cross sections:

$$\sigma = \frac{2}{\cos \theta_{\max} - \cos \theta_{\min}} \int_{\cos \theta_{\min}}^{\cos \theta_{\max}} \frac{d\sigma(\theta)}{d\cos \theta} d\cos \theta$$

 $\cos \theta_{\min} = -0.5; \cos \theta_{\max} = 0.5$

fss2 ... Fujiwara et al. (constitutent quark model) Jülich 04, Nijmegen NSC97f ... meson-exchange potentials

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Results for SMS YN interactions

Σ⁺p (T. Nanamura et al., PTEP 2022 (2022) 093D01)



LECs in the ${}^{1}S_{0}$, ${}^{3}S_{1}$ - ${}^{3}D_{1}$ fixed from low-energy cross sections

SMS NLO: LECs in ³*P*-waves taken over from *NN* fit (RKE) (strict SU(3) symmetry: $V_{NN} \equiv V_{\Sigma^+\rho}$ in the ¹*S*₀, ³*P*_{0,1,2} partial waves!)

SMS NNLO: LECs in P-waves fitted to the E40 data (two examples)!

data for (550 $\leq p \leq$ 650) MeV/c are overestimated (influence of Λp_{π}^+ threshold?)

Results for SMS YN interactions



 $\Sigma^- p \rightarrow \Lambda n$: quite well reproduced by NLO19 (NLO13) and SMS YN potentials $\Sigma^- p \rightarrow \Sigma^- p$: behavior at forward angles remains unclear

 $\Sigma^- \rho$ and $\Sigma^- \rho \to \Lambda n$ data for (550 $\leq \rho \leq$ 650) MeV/c are reproduced with comparable quality

- no unique determination of all *P*-wave LECs possible
- one needs data from additional channels ($\Lambda p, \Sigma^- p \rightarrow \Sigma^0 n, ...$)
- one needs additional differential observables (polarizations, ...)

Hypernuclei within the NCSM

ab initio no-core shell model (NCSM)

Basic idea: use harmonic oscillator states and soft interactions

- m-scheme uses single particle states (center-of-mass motion not separated)
- antisymmetrization for nucleons easily performed (Slater determinant)
- Iarger dimensions (applications to p-shell hypernuclei by Wirth & Roth)

Jacobi-NCSM

- uses relative (Jacobi) coordinates (Hoai Le et al., EPJA 56 (2020) 301)
- explicit separation of center-of-mass motion possible
- antisymmetrization for nucleons difficult but feasible for $A \leq 9$
- small dimensions

Soft interactions: Similarity renormalization group (SRG) (unitary transformation)

$$\frac{dH(s)}{ds} = [[T, H(s)], H(s)] \qquad H(s) = T + V(s) \qquad V(s) : V^{NN}(s), V^{YN}(s)$$

- Flow equations are solved in momentum space
- parameter (cutoff) $\lambda = \left(4\mu_{BN}^2/s\right)^{1/4}$ is a measure of the width of the interaction in momentum space
- V(s) is phase equivalent to original interaction
- transformation leads to induced 3BFs, 4BFs, ...

(induced 3BFs included in the work of Wirth & Roth and in our recent studies) (induced 4BFs are most likely very small)

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Procedure

slide from Hoai Le:

· extrapolation of energies:



▶ strong correlations between $E_{nucl}(\mathcal{N}), E_{hypnucl}(\mathcal{N})$

$$B_{\Lambda,\mathcal{N}} = E_{nucl}(\mathcal{N}) - E_{hypnucl}(\mathcal{N})$$
$$B_{\Lambda,\mathcal{N}} = B_{\Lambda,\infty} + A_1 e^{-b_1 \mathcal{N}}$$

HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 56 (2020)



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Results for $B_{\Lambda}(A \leq 8)$

Hoai Le et al., PRC 107 (2023) 024002

- NLO13 and NLO19 are almost phase equivalent in the 2-body sector
- NLO13 characterised by a stronger $\Lambda N \Sigma N$ transition potential (especially in ${}^{3}S_{1}$)



signal for (missing) chiral YNN forces

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Charge symmetry breaking in the ΛN interaction

J.H., U.-G. Meißner, A. Nogga, FBS 62 (2021) 105



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CSB results for A=4,7,8 hypernuclei

Hoai Le, J.H., U.-G. Meißner, A. Nogga, PRC 107 (2023) 024002



NN:SMS N⁴LO+(450) +3N: N²LO(450) +YN: NLO13,19(CSB) +SRG-induced YNN

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NLO13 & NLO19 CSB results for A=7 are comparable to experiment.

- two potentials predict a somewhat larger CSB in A=8 doublet as compared to experiment
 - experimental CS splitting for A=8 could be larger than 40 ± 60 keV?
 - CSB estimate for A = 4 too large? different spin-dependence?

Consider new Star measurement

STAR Collaboration (M. Abdallah et al.), PLB 834 (2022) 137449

Recent Star measurement suggests somewhat different CSB in A=4:

$\Delta E(1^+) = B_{\Lambda}(^4_{\Lambda}\text{He}, 1^+) - B_{\Lambda}(^4_{\Lambda}\text{H}, 1^+)$		NLO19(500)	CSB	CSB*
$= -83 \pm 94 \text{ keV} \Rightarrow (CSB)$	a_s^{Ap}	-2.91	-2.65	-2.58
$= -160 \pm 140 \pm 100 \text{ keV} \Rightarrow (\text{CSB}^*)$	$a_s^{\Lambda n}$	-2.91	-3.20	-3.29
·	δa_s	0	0.55	0.71
$\Delta E(0^+) = B_{\Lambda}({}^{4}_{\Lambda}\text{He}, 0^+) - B_{\Lambda}({}^{4}_{\Lambda}\text{H}, 0^+)$	a_t^{Ap}	-1.42	-1.57	-1.52
$= 233 \pm 92 \text{ keV} \Rightarrow (CSB)$	$a_t^{\Lambda n}$	-1.41	-1.45	-1.49
$= 160 \pm 140 \pm 100 \text{ keV} \Rightarrow (\text{CSB}^*)$	δa_t	-0.01	-0.12	-0.03
* STAR Collaboration PLB 834 (2022)	$\rightarrow \delta a(^1S$) increases wh	ile $\delta a({}^3S_1$) decrease

→ How does the STAR measurement affect the predictions of CSB in A=7,8 multiplets ?

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Impact of Star measurement on CSB in A=7,8



NN:SMS N⁴LO+(450) +YN: NLO13,19(CSB) $\lambda_{NN} = 1.6 \text{ fm}^{-1}$ $\lambda_{YN}^{opt} = 0.823 \text{ fm}^{-1}$ $B_{\Lambda}({}^{5}_{\Lambda}\text{He}, \lambda_{YN}^{opt}) = B_{\Lambda}({}^{5}_{\Lambda}\text{He}, 3\text{BFs})$

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- CSB* fit predicts reasonable CSB in both A=7 and A=8 systems
- CSB in A=4(0⁺) and A=8, and in A=4(1⁺) and A=7 are correlated

Separation energies for A=3-8 ∧ hypernuclei (MeV)

- NLO13(19), SMS NLO,N²LO are phase equivalent ($\chi^2 \approx 16$ for 36 YN data points)
- NLO13 characterized by a stronger $\Lambda N \cdot \Sigma N$ coupling potential $({}^{3}S_{1} \cdot {}^{3}D_{1})$

	³ _A H [Faddeev]	$^{4}_{\Lambda}$ He(0 ⁺)	$^{4}_{\Lambda}$ He(1 ⁺)	⁵ ∧He	7∧Li	8∧Li
NLO13	0.090	$\textbf{1.48} \pm \textbf{0.02}$	0.58 ± 0.02	2.22 ± 0.06	5.28 ± 0.68	5.75 ± 1.08
NLO19	0.091	1.46 ± 0.02	1.06 ± 0.02	3.32 ± 0.03	6.04 ± 0.30	$\textbf{7.33} \pm \textbf{1.15}$
SMS NLO	0.124	$\textbf{2.10} \pm \textbf{0.02}$	1.10 ± 0.02	3.34 ± 0.01		
SMS N ² LO	0.139	$\textbf{2.02} \pm \textbf{0.02}$	1.25 ± 0.02	3.71 ± 0.01		
Exp.*	0.148 ± 0.04	$\textbf{2.347} \pm \textbf{0.036}$	0.942 ± 0.036	3.102 ± 0.03	5.85 ± 0.13	$\textbf{6.80} \pm \textbf{0.03}$
					5.58 ± 0.03	

NN: SMS N⁴LO+(450) + 3NF: N²LO(450) + SRG-induced YNN force

NLO19 (600): ${}^{4}_{\Lambda}$ He(1⁺), ${}^{5}_{\Lambda}$ He, ${}^{7}_{\Lambda}$ Li fairly well described NLO13 (600) underestimates the separation energies SMS NLO,N²LO (550): ${}^{4}_{\Lambda}$ He(0⁺, 1⁺), ${}^{5}_{\Lambda}$ He fairly well described

chiral YNN forces appear at N²LO $\rightarrow \Lambda NN$: 5 LECs with decuplet saturation at NLO (LECs: 1 $\Lambda NN + 1 \Sigma NN$) \rightarrow could be fixed from separation energies of, e.g., $^{4}_{\Lambda}$ He (0⁺, 1⁺) or $^{4}_{\Lambda}$ He (0⁺, 1⁺), $^{5}_{\Lambda}$ He

* Chart of Hypernuclides https://hypernuclei.kph.uni-mainz.de/

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Uncertainty quantification

- Uncertainty for a given observable X(p): (Epelbaum, Krebs, Meißner, EPJA 51 (2015) 53)
 (S. Binder et al. [LENPIC coll.], PRC 93 (2016) 044002)
- estimate uncertainty via
 - the expected size of higher-order corrections
 - the actual size of higher-order corrections

$$\begin{split} \Delta X^{LO} &= Q^2 |X^{LO}| \quad (X^{NLO} \approx Q^2 X^{LO}) \\ \Delta X^{NLO} &= \max\left(Q^3 |X^{LO}|, Q^1 |\delta X^{NLO}|\right); \quad \delta X^{NLO} = X^{NLO} - X^{LO} \\ \Delta X^{N^2 LO} &= \max\left(Q^4 |X^{LO}|, Q^2 |\delta X^{NLO}|, Q^1 |\delta X^{N^2 LO}|\right); \quad \delta X^{N^2 LO} = X^{N^2 LO} - X^{NLO} \\ \Delta X^{N^3 LO} &= \max\left(Q^5 |X^{LO}|, Q^3 |\delta X^{NLO}|, Q^2 |\delta X^{N^2 LO}|, Q^1 |\delta X^{N^3 LO}|\right); \quad \delta X^{N^3 LO} = X^{N^3 LO} - X^{N^2 LO} \end{split}$$

expansion parameter Q is defined by

$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_{\pi}}{\Lambda_b}\right); \quad p \dots \Lambda p \text{ on } - \text{ shell momentum}$$

 Λ_b ... breakdown scale $\rightarrow \Lambda_b = 500 - 600$ MeV [for R = 0.8 - 1.2 fm] (EKM, 2015)

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Estimate of truncation error (preliminary!)



- filled symbols: actual estimates for SMS LO, NLO, N²LO YN potentials
- opaque symbols: anticipated results when YNN 3BFs are included
- ${}^{3}_{\Lambda}$ H: used as constraint! Conclusions on true uncertainty are not possible
- Q: $Q = M_{\pi}^{\text{eff}} / \Lambda_b \approx 200/650$ (Epelbaum et al., for light nuclei)

Hyperon-nucleon interaction within chiral EFT

ΛN-ΣN interaction within semilocal momentum-space regularized chiral EFT confirm our previous YN results (up to NLO) based on a nonlocal regulator successful extension to NNLO new Σ[±]p differential cross sections around p_{lab} ≈ 500 MeV/c can be described unique determination of the P-waves is not yet possible

Hypernuclei

- three-body forces: should be small for (³_{\Left}H) or moderate (⁴_{\Left}H, ⁴_{\Left}He, ⁵_{\Left}He) needs to be quantified/confirmed by explicit inclusion of 3BFs
- charge-symmetry breaking in ${}_{\Lambda}^{4}H {}_{\Lambda}^{4}He$ can be reproduced when taking into account the full leading CSB potential within chiral EFT
- charge-symmetry breaking in A = 7 8 A-hypernuclei predicted CSB splitting for ⁷_ABe, ⁷_ALi*, ⁷_AHe is in line with experiments CSB splitting for ⁸_ABe, ⁸_ALi is overestimated

∧p momentum correlation functions

 ALICE measurement: indications that the Λp is possibly somewhat weaker than what the cross section data from the 1960ies suggest (D. Mihaylov, M. Korwieser)

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