Hypernuclei and charmed nuclei

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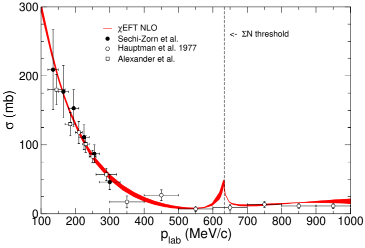
Outline

Interaction of strange baryons

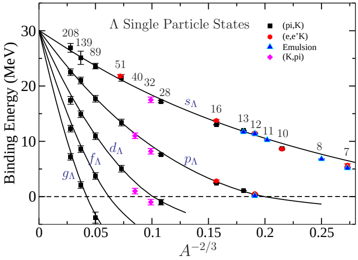
- ΛN and ΣN scattering
  $\rightarrow$ Role of SU(3) flavor symmetry
- H dibaryon
  - Jaffe (1977) $\rightarrow$ deeply bound 6-quark state with $I = 0$, $J = 0$, $S = -2$
  - many experimental searches but no convincing signal
  - Lattice QCD (2010) $\rightarrow$ evidence for a bound H dibaryon ($\Lambda\Lambda$)
- Few-body systems with hyperons: ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$, ...
  $\rightarrow$ Role of three-body forces
  large charge symmetry breaking ${}^{4}_{\Lambda}\mathrm{H} \leftrightarrow {}^{4}_{\Lambda}\mathrm{He}$
- (Λ, Σ) hypernuclei and hyperons in nuclear matter
  $\rightarrow$ very small spin-orbit splitting: weak spin-orbit force
  existence of Ξ hypernuclei
  repulsive Σ nuclear potential
- implications for astrophysics
  $\rightarrow$ hyperon stars
  stability/size of neutron stars
  softening of equation of state (hyperon puzzle)

ΛN interaction: bulk properties are known

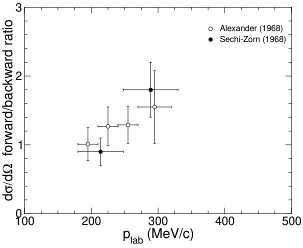
Λp cross section



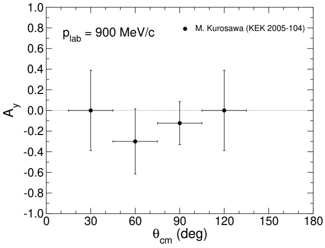
Λ hypernuclei



Λp -> Λp



Λp -> Λp



BB interaction in chiral effective field theory

Baryon-baryon interaction in SU(3) chiral effective field theory (χEFT)
à la Weinberg (1990) [up to next-to-leading order (NLO)]

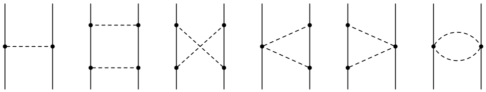
Advantages:

- 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)

Ingredients:

1) pseudoscalar-meson exchanges – similar to meson-exchange potentials

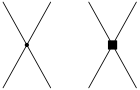


BB interaction in chiral effective field theory

2) short-distance dynamics remains unresolved – represented by contact terms
(involve low-energy constants (LECs) that need to be fixed from data)

$$V^{CT}_{B_1B_2\to B_1'B_2'} = \tilde{C}_\alpha + C_\alpha(p'^2+p^2) \quad (C_\beta p'^2,\ C_\gamma p' p)$$

$\alpha = {}^1S_0, {}^3S_1;\ \beta = {}^3S_1 - {}^3D_1;\ \gamma = {}^3P_0, {}^1P_1, {}^3P_1, {}^3P_2$



No. of LECs is limited by SU(3) flavor symmetry:
6 at LO + 22 at NLO (in total) [for NN, ΛN, ΣN, $\Lambda\Lambda$, ΞN, ..., $\Xi\Xi$]
5 at LO + 5 at NLO (for *S*-waves; dominant for ΛN and ΣN scattering at low energies)

- NLO interaction from 2013 (J.H. et al., NPA 915 (2013) 24)

  fix all *S*-wave LECs from a fit directly to available
  low-energy Λp and ΣN scattering data ($\approx$ 36 data points)
  no SU(3) constraints from the *NN* interaction (except for *P*-waves)

  $\Rightarrow$ excellent description of data is achieved ($\chi^2 \approx 16 - 17$)
- NLO interaction from 2019 (J.H. et al., EPJA 56 (2020) 91)

  consider SU(3) constraints from the *NN* interaction:
  2 (NLO) LECs are fixed from the ${}^1S_0$ and ${}^3S_1$ *NN* phase shifts

- explore consequences for the *YN* interaction (uncertainties)
- explore consequences for hypernuclei (role of three-body forces)

Coupled channels Lippmann-Schwinger Equation

$$T^{\nu'\nu,J}_{\rho'\rho}(p',p) = V^{\nu'\nu,J}_{\rho'\rho}(p',p) + \sum_{\rho'',\nu''}\int_0^\infty \frac{dp''p''^2}{(2\pi)^3}\, V^{\nu'\nu'',J}_{\rho'\rho''}(p',p'')\frac{2\mu_{\rho''}}{p^2-p''^2+i\eta}\, T^{\nu''\nu,J}_{\rho''\rho}(p'',p)$$

$\rho',\ \rho = \Lambda N,\ \Sigma N\quad (\Lambda\Lambda,\ \Xi N,\ \Lambda\Sigma,\ \Sigma\Sigma)$

LS equation is solved for particle channels (in momentum space)

Coulomb interaction is included via the Vincent-Phatak method

The potential in the LS equation is cut off with the regulator function:

$$V^{\nu'\nu,J}_{\rho'\rho}(p',p) \to f^\Lambda(p')\,V^{\nu'\nu,J}_{\rho'\rho}(p',p)f^\Lambda(p);\quad f^\Lambda(p) = e^{-(p/\Lambda)^4}$$

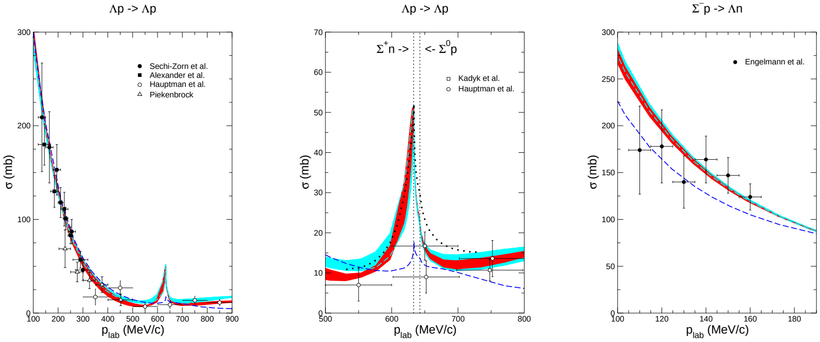
consider values $\Lambda = 500$ - 650 MeV [guided by *NN*, achieved χ^2]

ideally the regulator (Λ) dependence should be absorbed completely by the LECs

in practice there is a residual regulator dependence (shown by bands below)

- tells us something about the convergence
- tells us something about the size of higher-order contributions

YN integrated cross sections



NLO13: J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24

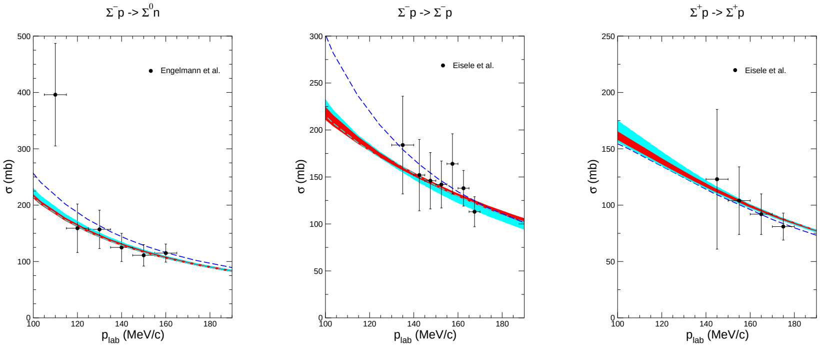
NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

Jülich '04: J.H., U.-G. Meißner, PRC 72 (2005) 044005

Nijmegen NSC97f: T.A. Rijken et al., PRC 59 (1999) 21

data points included in the fit are represented by filled symbols!

YN integrated cross sections



NLO13: J.H. et al., NPA 915 (2013) 24

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Nijmegen NSC97f: T.A. Rijken et al., PRC 59 (1999) 21

YN scattering lengths [fm]

	NLO13	NLO19	Jülich '04	NSC97f	experiment*
Λ [MeV]	$500 \cdots 650$	$500 \cdots 650$			
$a_s^{\Lambda p}$	$-2.91 \cdots -2.90$	$-2.91 \cdots -2.90$	-2.56	-2.51	$-1.8^{+2.3}_{-4.2}$
$a_t^{\Lambda p}$	$-1.61 \cdots -1.51$	$-1.52 \cdots -1.40$	-1.66	-1.75	$-1.6^{+1.1}_{-0.8}$
$a_s^{\Sigma^+ p}$	$-3.60 \cdots -3.46$	$-3.90 \cdots -3.43$	-4.71	-4.35	
$a_t^{\Sigma^+ p}$	$0.49 \cdots 0.48$	$0.48 \cdots 0.42$	0.29	-0.25	
χ^2	$15.7 \cdots 16.8$	$16.0 \cdots 18.1$	≈ 22	16.7	
$B(^3_\Lambda\mathrm{H})$	$-2.30 \cdots -2.33$	$-2.32 \cdots -2.32$	-2.27	-2.30	$-2.354(50)$

*G. Alexander et al., PR 173 (1968) 1452

Note: $B(^3_\Lambda\mathrm{H})$ is used as additional constraint in EFT and Jülich '04
Λp data alone do not allow to disentangle $^1S_0$ (s) and $^3S_1$ (t) contributions

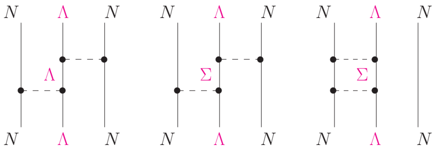
(a, r in fm; B in MeV)

Difference between NLO13 and NLO19

Different coupling strength between the ΛN and ΣN channels ($V_{\Lambda N \leftrightarrow \Sigma N}$)

consequences for in-medium properties:
ΛN–ΣN coupling is suppressed for increasing number of nucleons

dispersive effects in few-body systems:



$V^{eff}_{\Lambda N}(E) \approx V_{\Lambda N} + V_{\Lambda N \to \Sigma N} \, \frac{1}{E - H_0} \, V_{\Sigma N \to \Lambda N}$

(propagator includes the energy of the spectator nucleons!)

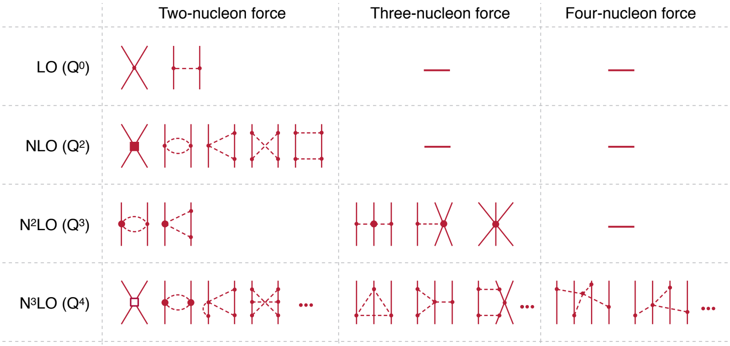
Pauli blocking effects in nuclear matter:

$V^{eff}_{\Lambda N}(\epsilon) \approx V_{\Lambda N} + V_{\Lambda N \to \Sigma N} \, \frac{Q}{\epsilon - H_0} \, V_{\Sigma N \to \Lambda N}$

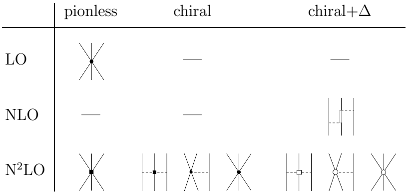
EFT: in consistent few- and many-body calculations, differences in the two-body potential (in the ΛN–ΣN coupling) are to be compensated by many-body forces

($\rightarrow$ tool for estimating effects from three-body forces!)

3- and many-body forces in chiral EFT (E. Epelbaum)

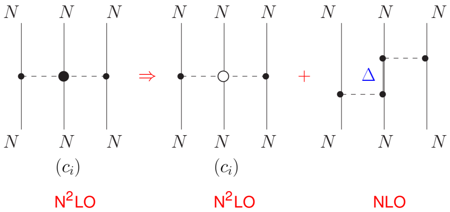


different hierarchy of 3BFs
for other counting schemes
(Hammer, Nogga, Schwenk,
Rev. Mod. Phys. 85 (2013) 197)



Three-nucleon forces: Explicit inclusion of the Δ(1232)

- Explicit treatment of the Δ (Krebs, Gasparyan, Epelbaum, PRC 98 (2018) 014003):



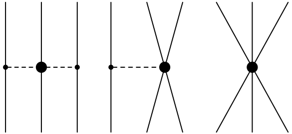
LECs (from πN)	c_1	c_2	c_3	c_4
Δ-less approach	-0.75	3.49	-4.77	3.34
Δ-full approach	-0.75	1.90	-1.78	1.50
Δ contribution	0	2.81	-2.81	1.40

- more natural size of LECs
- better convergence of EFT expansion (3NF from Δ(1232) appears at NLO!)
- applicability at higher energies

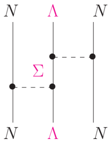
Three-body forces

- SU(3) χEFT 3BFs nominally at N^{2}LO (S. Petschauer et al., PRC 93 (2016) 014001)

SU(3) χEFT :

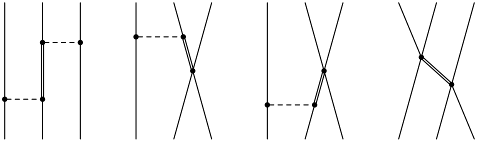


(at LO!) :



solve coupled channel (ΛN-ΣN) Faddeev-Yakubovsky equations:
$\Rightarrow$ ΛNN "3BF" from Σ coupling is automatically included
remaining 3BF expected to be small

- ΛNN 3BF via Σ^* excitation in SU(3) χEFT with $\{10\}$ baryons (NLO)



estimate ΛNN 3BF based on the $\Sigma^*(1385)$ excitation (S. Petschauer et al., NPA 957 (2017) 347)

Hypernuclei studies based on chiral EFT potentials

Goal: perform few- and many-body calculations that take into account the full complexity of the underlying YN interaction (tensor coupling, ΛN-ΣN coupling, ...) in a consistent framework

- Faddeev-Yakubovsky calculations

  feasible only up to $A = 4$: ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H (0^{+}), ${}^{4}_{\Lambda}$H (1^{+}), ${}^{4}_{\Lambda}$He (0^{+}), ${}^{4}_{\Lambda}$He (1^{+})
  so far no (explicit) 3BFs included
  (Andreas Nogga, Jülich)

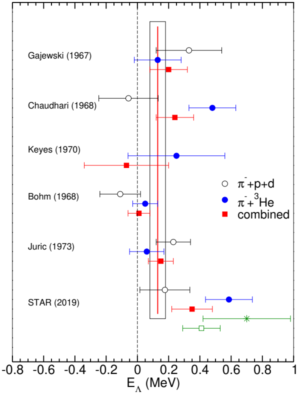
- No-core shell model (NCSM)

  calculations for LO interaction
  hypernuclei up to ${}^{13}_{\Lambda}$C have been considered
  (Wirth & Roth, PRL 117 (2016) 182501, PRC 100 (2019) 044313)
  so far no (explicit) 3BFs included

  calculations for NLO interaction
  hypernuclei up to ${}^{7}_{\Lambda}$Li have been considered
  (Hoai Le, PhD thesis, Jülich 2020; arXiv:2008.11565)
  so far no 3BFs included

Status - hypertriton

$$^3_\Lambda\mathrm{H} \rightarrow \pi^- + p + d, \rightarrow \pi^- + {}^3\mathrm{He}$$

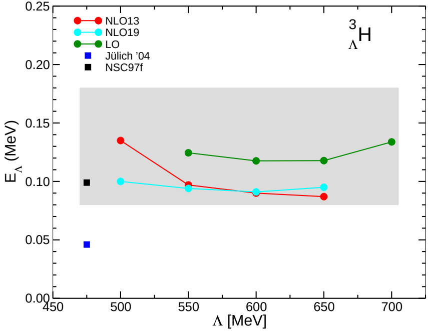


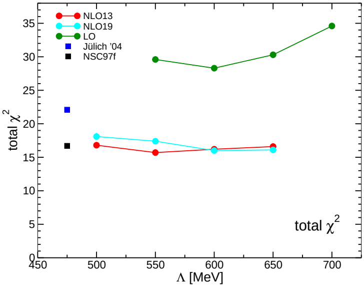
benchmark: (M. Jurič et al., 1973): 0.13 $\pm$ 0.05 MeV

STAR (J. Adam et al., Nature Phys. 16 (2020) 409) ($^3_\Lambda\mathrm{H}$+$^3_\Lambda\bar{\mathrm{H}}$): 0.41 $\pm$ 0.12 $\pm$ 0.11 MeV

(separation energy $E_\Lambda = B_\Lambda - B_d$)

Hypertriton (Faddeev calculation by A. Nogga)





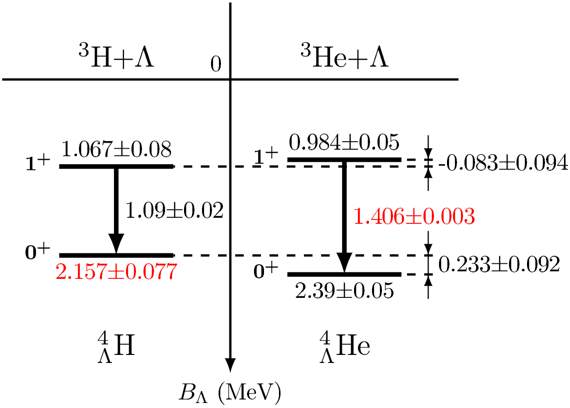
- Λp $^1S_0$ / $^3S_1$ scattering lengths are chosen so that $^3_\Lambda$H is bound
- cutoff variation:

* NNN → is lower bound for magnitude of higher order contributions

* ΛNN - correlation with χ^2 of YN interaction

⇒ effect of three-body forces small?

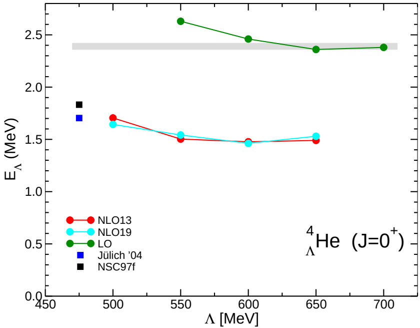
NN potential: SMS N^{4}LO+ (450) (P. Reinert et al., EPJA 54 (2018) 86)

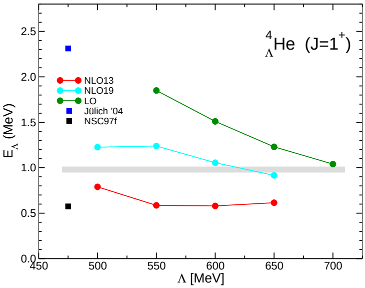


large CSB in 0^+ ($\Delta \approx 233$ keV), small CSB in 1^+ ($\Delta \approx -83$ keV)

F. Schulz et al. [A1 Collaboration] (2016), T.O. Yamamoto et al. [J-PARC E13 Collaboration] (2015)

${}^{4}_{\Lambda}$He results (Faddeev-Yakubovsky – by A. Nogga)





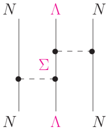
- LO: unexpected small cutoff dependence in 0^{+} result
- NLO: underbinding in χEFT and for phenomenological potentials
- possible effects of long ranged three-body forces?

  (no CSB in χEFT YN potentials!)

Estimation of 3BFs based on NLO results

- ${}^{3}_{\Lambda}$H
  (a) cutoff variation: ΔE_Λ (3BF) $\leq$ 50 keV
  (b) "3BF" from ΛN-ΣN coupling:

  switch off ΛN-ΣN coupling
  in Faddeev-Yakubovsky equations:
  ΔE_Λ (3BF) $\approx$ 10 keV
  expect similar/smaller ΔE_Λ from $\Sigma^*(1385)$ excitation



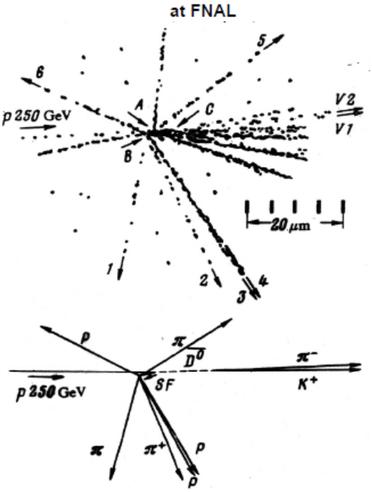
  (c) ^{3}H: 3NF $\sim Q^3 \, |\langle V_{NN}\rangle|_{^3\mathrm{H}} \sim$ 650 keV
  ($|\langle V_{NN}\rangle|_{^3\mathrm{H}} \sim$ 50 MeV; $Q \sim m_\pi/\Lambda_b$; $\Lambda_b \simeq$ 600 MeV)
  ${}^{3}_{\Lambda}$H: $|\langle V_{\Lambda N}\rangle|_{^3_\Lambda\mathrm{H}} \sim$ 3 MeV $\rightarrow \Delta E_\Lambda$ (3BF) $\approx Q^3 \, |\langle V_{\Lambda N}\rangle|_{^3_\Lambda\mathrm{H}} \simeq$ 40 keV

- ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He
  (a) cutoff variation: ΔE_Λ (3BF) $\approx$ 200 keV (0^+) and $\approx$ 300 keV (1^+)
  (b) "3BF" from ΛN-ΣN coupling:
  ΔE_Λ (3BF) $\approx$ 230 – 340 keV (0^+), $\approx$ 150 – 180 keV (1^+)

${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H(He) calculations with explicit inclusion of 3BFs are planned for the future

A possible case of a charmed nucleus

Y.A. Batusov et al., JETP Lett. 33 (1981) 52



p + Emulsion → "Charmed HY" + $\bar{D}^0$ + X
|→ $K^+\pi^-$

Interpretations

① $^4_{\Lambda_c^+}\mathrm{Be} \rightarrow \Lambda^o{}_s\,\pi^+\pi^+\pi^- p\,p\,p$

($\Lambda^+{}_c \rightarrow \Lambda^o{}_s\,\pi^+\pi^+\pi^-$)

Bc = 0 ~ 10 MeV

② $^4_{\Lambda_c^+}\mathrm{He} \rightarrow \Lambda^o{}_s\,\pi^+\pi^+\pi^o p\,p\,p$

($\Lambda^+{}_c\, n \rightarrow \Lambda^o{}_s\, p\,\pi^+\pi^+\pi^o$)

⊕ $\pi^o n \rightarrow \pi^+ p$

Bc = 0 ~ 10 MeV

③ $^{6+k}_{\Lambda_c^+}\mathrm{C} \rightarrow \Lambda_s\,\pi^+\,\pi^+\,\pi^+ ppp\; nn + kn\; (k>=1)$

($\Lambda^+{}_c\, p \rightarrow \Lambda^o{}_s\, n\,\pi^+\pi^+\pi^o$)

⊕ $\pi^o p \rightarrow \pi^+ n$

Bc = ?

A: primary vertex B: vertex decay of a charmed nucleus
C: decay of $\bar{D}^0$ – signal of $c\bar{c}$ pair production

Λ_c-nucleon interaction and charmed nuclei

- Many model calculations

  meson-exchange picture, constitutent quark model, ...
  SU(4) flavor symmetry, ...

  - Dover & Kahana, PRL 39 (1977) 1506
  - S. Iwao, Lett. Nuovo Cim. 19 (1977) 647
  - H. Bando & M. Bando, PLB 109 (1982) 1604
  - Gibson, Bhamathi, Dover & Lehman, PRC 27 (1983) 2085

  .

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  - Liu & Oka, PRD 85 (2012) 014015
  - Huang, Ping & Wang, PRC 87 (2013) 034002 (2013)
  - Gal, Garcilazo, Valcarce & Caramés, PRD 90 (2014) 014019
  - Garcilazo, Valcarce & Caramés, PRC 92 (2015) 024006
  - Maeda, Oka, Yokota, Hiyama & Liu, PTEP 2016 (2016) 023D2
  - Ohtani, Araki & Oka, PRC 96 (2017) 055208
  - Vidaña, Ramos & Jiménez-Tejero, PRC 99 (2019) 045208
  - Garcilazo, Valcarce & Caramés, EPJC 79 (2019) 598

- ... but no empirical information

$\Lambda_c N$ results from recent phenomenological models

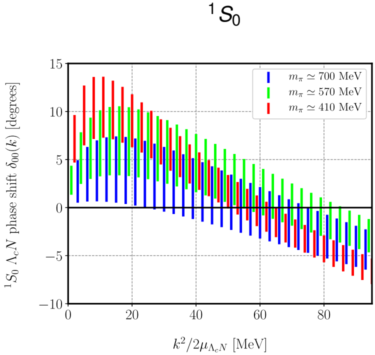
	scattering length (fm)		binding (separation) energy (MeV)			
$\Lambda_c N$	a_s	a_t	$\Lambda_c N$	${}^{3}_{\Lambda_c}$He	${}^{4}_{\Lambda_c}$He	${}^{5}_{\Lambda_c}$Li
CTNN-d (Maeda)	5.31	5.01	$\approx$ 5.3	$\approx$ 20	?	?
Model A (Vidaña)	-2.60	-15.87	-	?	?	13.58
CQM (Garcilazo)	-0.86	-2.31	-	0.14	?	?
ΛN	a_s	a_t	ΛN	${}^{3}_{\Lambda}$H	${}^{4}_{\Lambda}$He	${}^{5}_{\Lambda}$He
χEFT NLO19	-2.91	-1.52	-	0.10	1.63	$\approx$ 3.1
experiment			-	0.13(5)	2.39(3)	3.12(2)

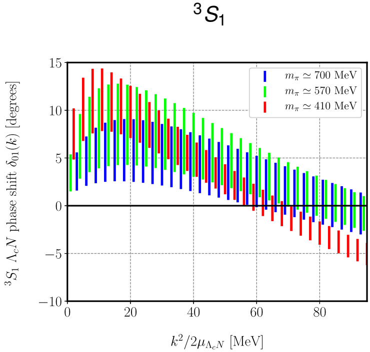
Note: $\Lambda_c \equiv \Lambda_c^+ \Rightarrow$ additional Coulomb repulsion

Maeda, Oka, Yokota, Hiyama & Liu, PTEP 2016 (2016) 023D2 - combined meson/quark exchange model
Vidaña, Ramos & Jiménez-Tejero, PRC 99 (2019) 045208 - meson exchange (Jülich YN model + SU(4) symmetry)
Garcilazo, Valcarce & Caramés, EPJC 79 (2019) 598 - constituent quark model

$\Lambda_c N$ results from lattice QCD simulations

HAL QCD: T. Miyamoto et al., NPA 971 (2018) 113





$a_s = -0.13 \pm 0.11$ fm $a_t = -0.17 \pm 0.10$ fm (at $m_\pi = 700$ MeV)

$a_s = -0.24 \pm 0.13$ fm $a_t = -0.29 \pm 0.16$ fm (at $m_\pi = 570$ MeV)

$a_s = -0.49 \pm 0.18$ fm $a_t = -0.51 \pm 0.20$ fm (at $m_\pi = 410$ MeV)

Extrapolation of lattice results to physical pion mass

construct $\Lambda_c N$-$\Sigma_c N$ potential in analogy to the ΛN-ΣN interaction
perform extrapolation in line with chiral EFT

(JH, G. Krein, EPJA 54 (2018) 199)

$$V^{OPE}_{BN\to B'N} = -f_{BB'\pi}(m_\pi^2) f_{NN\pi}(m_\pi^2) \frac{(\sigma_1 \cdot \mathbf{q})(\sigma_2 \cdot \mathbf{q})}{\mathbf{q}^2 + m_\pi^2} \mathcal{I}_{BN\to B'N}$$

$$V^{CT}_{BN\to B'N} = \tilde{C}_\alpha + C_\alpha (p'^2 + p^2)$$

$\tilde{C}_\alpha \to \tilde{C}_\alpha + \tilde{D}_\alpha m_\pi^2$, $\quad C_\alpha \to C_\alpha + D_\alpha m_\pi^2$, $\quad \alpha$ ... ${}^1S_0$, ${}^3S_1$

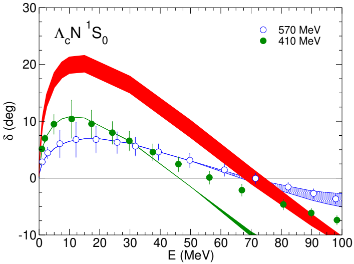
B, B' ... Λ_c, Σ_c

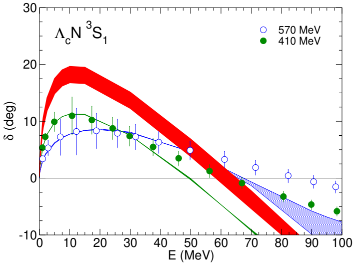
$f_{BB'\pi}(m_\pi^2)$, $f_{NN\pi}(m_\pi^2)$ ... are taken from lattice simulations

$\tilde{C}_\alpha$, $\tilde{D}_\alpha$, ... fitted to HAL QCD results at $m_\pi = 570,\ 410$ MeV

Extrapolation of lattice results to physical pion mass

JH, G. Krein, EPJA 54 (2018) 199





$a_s = -0.85 \cdots -1.00$ fm $\quad a_t = -0.81 \cdots -0.98$ fm $\quad$ (at $m_\pi = 138$ MeV)

Our predictions for charmed nuclei

JH, A. Nogga, I. Vidaña, EPJA 56 (2020) 56

- Few-body (Faddeev-Yakubovsky) calculation
  - ${}^{3}_{\Lambda_c}$He unbound - for $J^P = \frac{1}{2}^+, \frac{3}{2}^+$
  - ${}^{4}_{\Lambda_c}$He bound - for $J^P = 1^+$: $E_{\Lambda_c} \approx 0.10 - 0.40$ MeV
  - ${}^{4}_{\Lambda_c}$He possibly bound - for $J^P = 0^+$: $E_{\Lambda_c} \approx 0.00 - 0.10$ MeV
- perturbative many-body approach
  evaluate the energies of Λ_c single-particle bound states
  - ${}^{5}_{\Lambda_c}$Li and heavier charmed nuclei are bound

$E_{\Lambda_c} \approx 2.78 - 3.71$ MeV (${}^{13}_{\Lambda_c}$N) - core nucleus: ^{12}C

$E_{\Lambda_c} \approx 0.59 - 0.86$ MeV (${}^{5}_{\Lambda_c}$Li) - core nucleus: ^{4}He
$E_{\Lambda_c} \approx 2.78 - 3.71$ MeV (${}^{13}_{\Lambda_c}$N) - core nucleus: ^{12}C
$E_{\Lambda_c} \approx 4.35 - 6.36$ MeV (${}^{41}_{\Lambda_c}$Sc) - core nucleus: ^{40}Ca
$E_{\Lambda_c} \approx 2.15 - 4.89$ MeV (${}^{209}_{\Lambda_c}$Bi) - core nucleus: ^{208}Pb

Note: Coulomb contribution (repulsion) increases with increasing atomic number Z

Summary

Hyperon-nucleon interaction constructed within chiral EFT

- Approach is based on a modified Weinberg power counting, analogous to applications for *NN* scattering
- The potential (contact terms, pseudoscalar-meson exchanges) is derived imposing $SU(3)_f$ constraints
- $S = -1$: Excellent results at next-to-leading order (NLO)
  Λp, ΣN low-energy data are reproduced with a quality comparable to phenomenological models

Hypernuclei and charmed nuclei

- for very light hypernuclei three-body forces should be small (${}^{3}_{\Lambda}\mathrm{H}$) or moderate (${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$)
  needs to be quantified/confirmed by explicit inclusion of 3BFs
- ${}^{5}_{\Lambda}\mathrm{He}$, etc. ... effects of three-body forces could be more significant
- Study of charge-symmetry breaking in ${}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}$ is under way
- Λ hypernuclei - data with higher precision are needed to quantify 3BFs
- charmed (Λ_c) nuclei - any additional empirical information is useful
- (same is true for double-Λ hypernuclei!)