Baryonic forces in SU(3) chiral effective field theory

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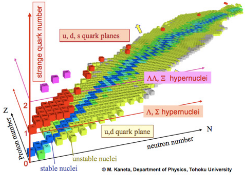
2. Hyperon-nucleon interaction at NLO
3. Chiral three-baryon forces
4. Summary / Outlook

Motivation

- Goal: determine interactions between hyperons (Y) and nucleons (N), e.g. important for:
  - hyperon-nucleon scattering
  - hypernuclei
  - strange baryons in nuclear matter



- accurate description of nuclear interactions with SU(2) chiral effective field theory [Epelbaum, Glöckle, Meißner, Entem, Machleidt, . . .]

  extend SU(2) χEFT to include strangeness
  $\Rightarrow$ SU(3) chiral effective field theory

- Advantages:
  - can improve results systematically
  - can derive consistently two- and three-baryon forces

Motivation

- systematic *NLO* analysis of chiral *contact terms* and *one*- and *two-meson exchange* contributions to baryon-baryon interactions using SU(3) χEFT

  Leading order (LO):

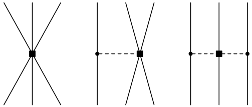
  [Polinder, Haidenbauer, Meißner, Nucl.Phys. A779, 2006]

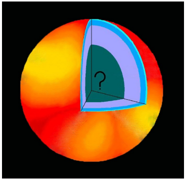
  Next-to-leading order (NLO):

  [Haidenbauer, Petschauer, Kaiser, Meißner, Nogga, Weise, Nucl.Phys. A915, 2013]

- repulsive ΛNN force suggested to get stiffer equation of state for neutron stars and to describe hypernuclei

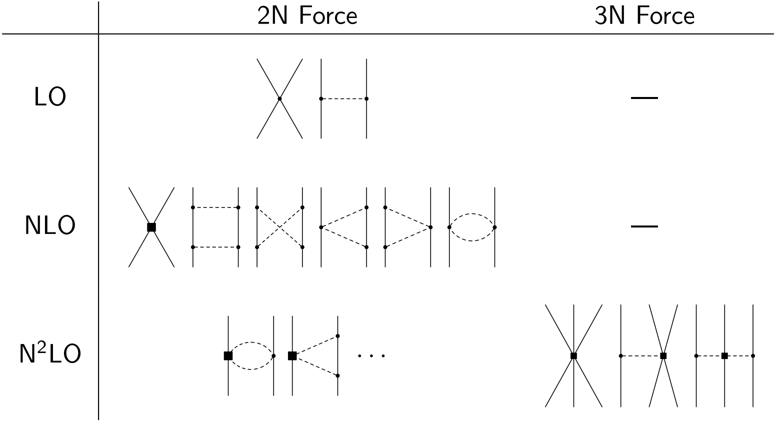
  [Gal et al.,Ann.Phys.63,1971] [Lonardoni et al.,Phys.Rev.C87,2013]





[http://www.astro.umd.edu/~miller/nstar.html]

Hierarchy of nuclear forces

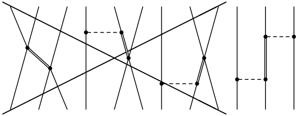
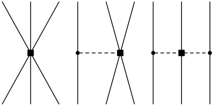


[van Kolck, Phys.Rev.C49, 1994]

[Epelbaum, Nogga, Glöckle, Kamada, Meißner, Witała, Phys.Rev.C66, 2002]

[Epelbaum, Hammer, Meißner, Rev.Mod.Phys.81, 2008]

Three-nucleon force including delta resonance

	3N Force with Δ isobar
LO	—
NLO	
N^2LO	 $+ \cdots$

[Epelbaum, Krebs and Meißner, Nucl.Phys.A806, 2008]

[Epelbaum, Hammer, Meißner, Rev.Mod.Phys.81, 2008]

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Chiral meson-baryon Lagrangian

Meson Lagrangian (in isospin limit $m_u = m_d \neq m_s$)

$$\mathscr{L}_{\mathrm{M}}^{(2)} = \frac{f_0^2}{4}\,\mathrm{tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \frac{1}{2} B_0 f_0^2\,\mathrm{tr}\left(M U^\dagger + U M\right)$$

$$U(x) = \exp\left(\mathrm{i}\frac{\phi(x)}{f_0}\right), \quad \phi = \begin{pmatrix} \pi^0 + \frac{\eta}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2\eta}{\sqrt{3}} \end{pmatrix}$$

Goldstone boson octet

$M \equiv \mathrm{diag}\,(m_u, m_d, m_s) \quad \Rightarrow \quad$ explicit SU(3)-breaking

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Goldstone boson octet

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Meson-baryon interaction

$$\mathscr{L}_{\mathrm{MB}}^{(1)} = \operatorname{tr}\left(\bar{B}\left(\mathrm{i}\not{D} - M_0\right) B - \frac{D}{2}\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\} - \frac{F}{2}\bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right)$$

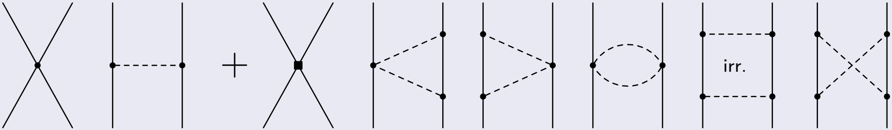
axial vector couplings:
$D \approx 0.8, \ F \approx 0.5$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

baryon octet

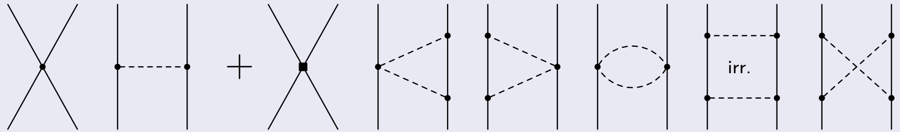
Deriving the T-matrix

Weinberg power counting for baryon-baryon potential

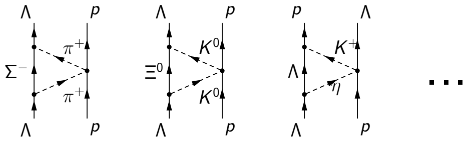


Deriving the T-matrix

Weinberg power counting for baryon-baryon potential

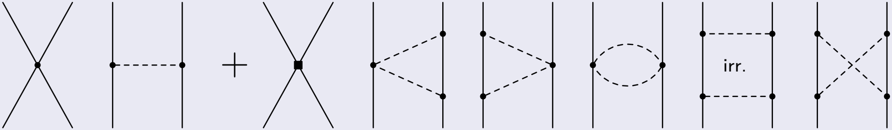


e.g.



Deriving the T-matrix

Weinberg power counting for baryon-baryon potential

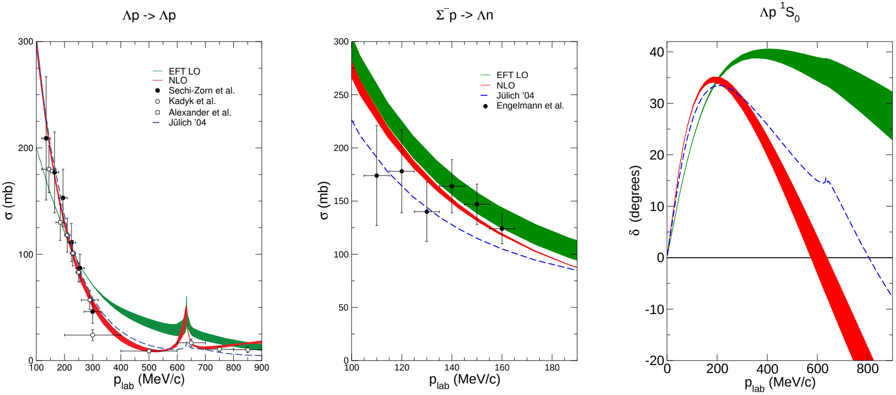


Coupled-channel Lippmann-Schwinger equation

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

ρ: partial wave $\quad$ ν: particle channel

Results for integrated cross sections and phase shifts



Included:

- one- and two-meson exchange; physical meson masses → SU(3) breaking
- LO and NLO contact terms
- Cutoff: 500 - 650 MeV
- LECs satisfy SU(3)

[Haidenbauer, Petschauer, Kaiser, Meißner, Nogga, Weise, Nucl.Phys. A915, 2013]

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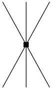
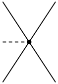
Constructing the chiral Lagrangian

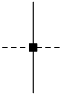
- symmetries of the effective Lagrangian:
  - chiral symmetry $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R}$
  - C, P, T, Hermitian conjugation
  - Lorentz transformation
- degrees of freedom:
  - pseudoscalar Goldstone boson octet (π, K, η)
  - baryon octet $(N, \Lambda, \Sigma, \Xi)$
  - baryon decuplet $(\Delta, \Sigma^*, \Xi^*, \Omega)$
- antisymmetrized potential to respect generalized Pauli principle
- vertices:



18 low-energy constants
(SU(3) symmetric)

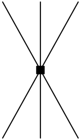


14 low-energy constants
[Petschauer, Kaiser, Nucl.Phys.A916, 2013]



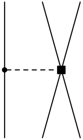
10 low-energy constants
[Krause, Helv.Phys.Acta 63, 1990]

Potentials for leading three-baryon forces

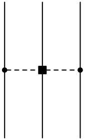


$$V^{\mathrm{ct}} = N_1\,\mathbb{1} + N_2\vec{\sigma}_1\cdot\vec{\sigma}_2 + N_3\vec{\sigma}_1\cdot\vec{\sigma}_3 + N_4\vec{\sigma}_2\cdot\vec{\sigma}_3 + N_5\mathrm{i}\,\vec{\sigma}_1\times\vec{\sigma}_2\cdot\vec{\sigma}_3$$

example: $V^{\mathrm{ct},\,I=0}_{\Lambda NN\to\Lambda NN} = c_1(\mathbb{1} + \frac{1}{3}\,\vec{\sigma}_2\cdot\vec{\sigma}_3) + c_2(\vec{\sigma}_1\cdot\vec{\sigma}_2 + \vec{\sigma}_1\cdot\vec{\sigma}_3)$



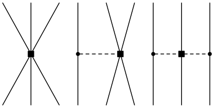
$$V^{1\phi} = -\frac{1}{2f_0^2}\frac{\vec{\sigma}_1\cdot\vec{q}_1}{\vec{q}_1^{\,2}+m_\phi^2}\left\{N_6\vec{\sigma}_2\cdot\vec{q}_1 + N_7\vec{\sigma}_3\cdot\vec{q}_1 + N_8\mathrm{i}\,(\vec{\sigma}_2\times\vec{\sigma}_3)\cdot\vec{q}_1\right\}$$



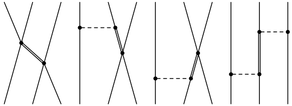
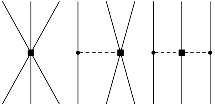
$$V^{2\phi} = \frac{1}{4f_0^2}\frac{\vec{\sigma}_1\cdot\vec{q}_1\;\vec{\sigma}_3\cdot\vec{q}_3}{(\vec{q}_1^{\,2}+m_{\phi_1}^2)(\vec{q}_3^{\,2}+m_{\phi_3}^2)} \times\left\{N_9 m_\pi^2 + N_{10}m_K^2 + N_{11}\vec{q}_1\cdot\vec{q}_3 + N_{12}\mathrm{i}\,\vec{\sigma}_2\cdot(\vec{q}_1\times\vec{q}_3)\right\}$$

$p_i(p_i')$ are initial (final) momenta of the baryon i and $\vec{q}_i \equiv \vec{p}_i\,' - \vec{p}_i$

Hierarchy of three-baryon forces

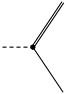
	3B Force
LO	—
NLO	—
N^2LO	

Hierarchy of three-baryon forces

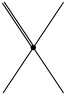
	3B Force with decuplet baryons
LO	—
NLO	
N^2LO	 $+ \cdots$

Three-baryon forces and explicit decuplet baryons

- new vertices:



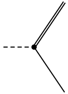
one constant ($C = \frac{3}{4} g_A \approx 1$ from $\Delta \to N\pi$)



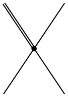
two constants (Pauli-forbidden in nucleonic sector)

Three-baryon forces and explicit decuplet baryons

- new vertices:



one constant ($C = \frac{3}{4} g_A \approx 1$ from $\Delta \rightarrow N\pi$)

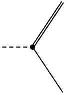


two constants (Pauli-forbidden in nucleonic sector)

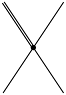
	tensor products in *flavor* space	and in *spin* space
final state	$\mathbf{10} \otimes \mathbf{8} = \mathbf{35} \oplus \mathbf{27} \oplus \mathbf{10} \oplus \mathbf{8}$	$\mathbf{3/2} \otimes \mathbf{1/2} = \mathbf{1} \oplus \mathbf{2}$

Three-baryon forces and explicit decuplet baryons

- new vertices:



one constant ($C = \frac{3}{4} g_A \approx 1$ from $\Delta \to N\pi$)



two constants (Pauli-forbidden in nucleonic sector)

	tensor products in *flavor* space	and in *spin* space
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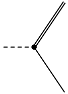
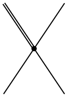
initial state	$\mathbf{8} \otimes \mathbf{8} = \underbrace{\mathbf{27} \oplus \mathbf{8_s} \oplus \mathbf{1}}_{\text{symmetric}} \oplus \underbrace{\mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8_a}}_{\text{antisymmetric}}$	$\mathbf{1/2} \otimes \mathbf{1/2} = \underbrace{\mathbf{0}}_{\text{a.sym.}} \oplus \underbrace{\mathbf{1}}_{\text{sym.}}$

Three-baryon forces and explicit decuplet baryons

- new vertices:



one constant ($C = \frac{3}{4} g_A \approx 1$ from $\Delta \to N\pi$)



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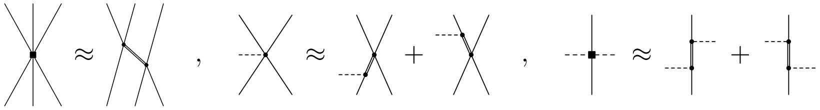
initial state	$\mathbf{8} \otimes \mathbf{8} = \underbrace{\mathbf{27} \oplus \mathbf{8_s} \oplus \mathbf{1}}_{\text{symmetric}} \oplus \underbrace{\mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8_a}}_{\text{antisymmetric}}$	$\mathbf{1/2} \otimes \mathbf{1/2} = \underbrace{\mathbf{0}}_{\text{a.sym.}} \oplus \underbrace{\mathbf{1}}_{\text{sym.}}$

- estimate chiral three-baryon forces via decuplet saturation:



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Summary

- SU(3) heavy baryon chiral effective field theory

- Hyperon-nucleon potentials at NLO including one- and two-meson exchange and contact terms with SU(3) symmetric LECs
- good description of available YN data; comparable to phenomenological models

- leading three-baryon forces constructed
- constants estimated through decuplet exchange $\Rightarrow$ only 2 unknown low-energy constants left

Outlook

- future applications of YN potential: hypernuclei, neutron star matter, hyperons in nuclear matter
- quantify effect of three-baryon forces in light hypernuclei