Hyperon-nucleon interaction and baryonic contact terms in SU(3) chiral effective field theory

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Motivation: SU(3) baryon chiral perturbation theory

- Goal: determine YN and YY interactions
  - empirical constraints from YN scattering and Λ hypernuclei
  - strange baryons in nuclear matter

- accurate description of nuclear interactions with SU(2) BχPT
  [Epelbaum, Machleidt, ...]
  extend SU(2) BχPT to include strangeness $\Rightarrow$ SU(3) BχPT

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

- Innovative work: YN and YY interactions in LO SU(3) BχPT by Jülich group
  [Polinder, Haidenbauer, Meißner, Nucl.Phys. A779, 2006]

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

Chiral meson-baryon Lagrangian

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

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

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

Goldstone boson octet

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

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Meson-baryon interaction

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

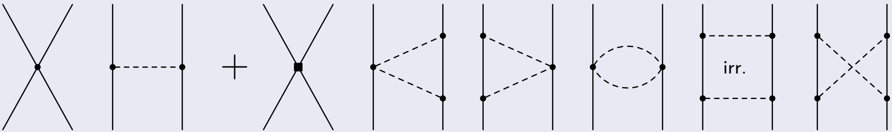
axial vector couplings:
$D \approx 0.8, \ F \approx 0.5$

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

baryon octet

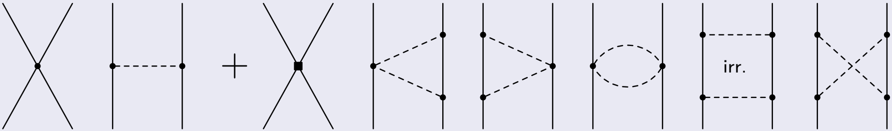
Deriving the T-matrix

Weinberg power counting for baryon-baryon potential

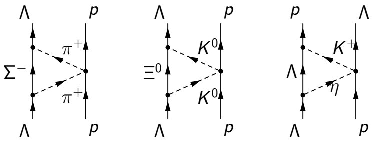


Deriving the T-matrix

Weinberg power counting for baryon-baryon potential



e.g.



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Deriving the T-matrix

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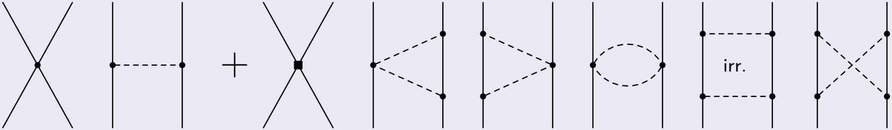
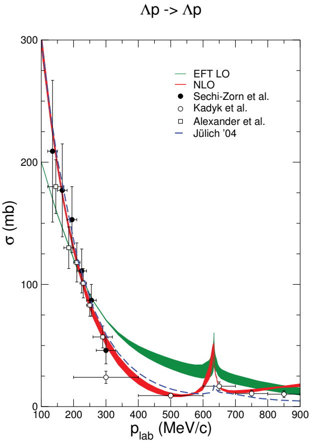


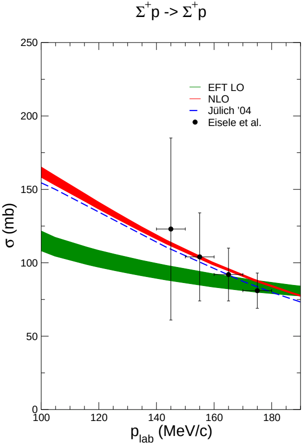
Coupled-channels Lippmann-Schwinger equation

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

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

Results for integrated cross section





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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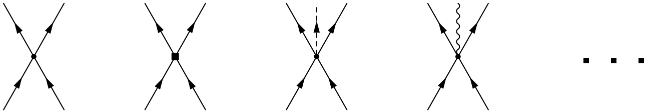
Construction of the Lagrangian



- external fields method for construction of Lagrangian [Gasser, Leutwyler]
- Lagrangian invariant under *local* transformations $\mathrm{SU}(3)_{\mathrm{L}} \times \mathrm{SU}(3)_{\mathrm{R}}$
- $U(x) = \exp\left(\mathrm{i}\frac{\phi(x)}{f_0}\right) \equiv u^2(x)\,, \qquad \phi$ meson octet
  $U \to RUL^\dagger$, $u \to RuK^\dagger = KuL^\dagger$, $\qquad K = K(L, R, U)$
- building blocks $u_\mu, \chi_+, \chi_-, f^+_{\mu\nu}, f^-_{\mu\nu}$ and baryon fields $B, \bar{B}$
  transform as $X \to KXK^\dagger$;
  same for covariant derivative $D_\mu X \to K(D_\mu X)K^\dagger$
- power counting [Krause, Helv.Phys.Acta 63, 1990]:
  $\mathcal{O}(p^0)$: $B,\ \bar{B},\ D_\mu B$; $\quad \mathcal{O}(p^1)$: $u_\mu,\ D_\mu$; $\quad \mathcal{O}(p^2)$: $f^+_{\mu\nu},\ f^-_{\mu\nu},\ \chi_+,\ \chi_-$
- construct all terms in the Lagrangian by traces of products of building block, or products of such traces

Baryon-baryon contact terms up to NLO

for pure baryon-baryon interactions:

$$f^{\pm}_{\mu\nu} = 0, \qquad \chi_- = 0, \qquad \chi_+ = 4B_0\,\mathrm{diag}(m_u, m_d, m_s), \qquad D_\mu = \partial_\mu$$

- $\mathcal{O}(p^0)$: $\langle \bar{B}_1(\gamma_5\gamma_\mu B_1)\bar{B}_2(\gamma_5\gamma^\mu B_2)\rangle\,, \ldots$ (18 terms)
- $\mathcal{O}(p^1)$: (1 terms)

$$\hat{\partial}_2^\alpha \langle \bar{B}_1 \bar{B}_2 (\gamma_5\gamma_\alpha\partial_\mu B)_1(\gamma_5\gamma^\mu B)_2\rangle + \hat{\partial}_1^\alpha \langle \bar{B}_1(\partial_\mu \bar{B})_2(\gamma_5\gamma^\mu B)_1(\gamma_5\gamma_\alpha B)_2\rangle$$

$\Rightarrow$ antisymmetric spin-orbit term: $\mathrm{i}\,(\vec{\sigma}_1 - \vec{\sigma}_2)\cdot(\vec{p}\times\vec{p}\,')$

$\Rightarrow$ spin singlet-triplet transitions: ${}^1P_1 \leftrightarrow {}^3P_1$

- $\mathcal{O}(p^2)$ (no external fields): $\langle \bar{B}_1 B_1 \partial^2(\bar{B}_2 B_2)\rangle\,, \ldots$ (9 terms)
- $\mathcal{O}(p^2)$ (with χ_+): $\langle \bar{B}_1 \chi_+ B_1 \bar{B}_2 B_2\rangle\,, \ldots$ (12 terms)

[Petschauer, Kaiser, Nucl.Phys.A916, 2013]

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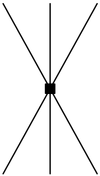
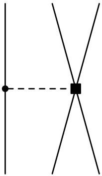
Leading order three-nucleon forces

short-range:



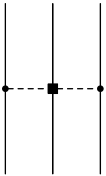
c_E

mid-range:



c_D

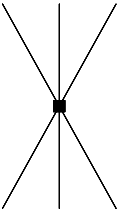
long-range:



c_1, c_3, c_4

[van Kolck, Epelbaum, Machleidt, . . .]

Classification of three baryon contact terms



- $B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$
- possible Dirac structures
  $\mathbb{1}, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}$
- leads after non-relativistic expansion to potentials of the form
  $\mathbb{1}\,,\ \vec{\sigma}_1 \cdot \vec{\sigma}_2\,,\ \vec{\sigma}_1 \cdot \vec{\sigma}_3\,,\ \vec{\sigma}_2 \cdot \vec{\sigma}_3\,,\ \vec{\sigma}_1 \times \vec{\sigma}_2 \cdot \vec{\sigma}_3$

- Lagrangian terms

$$\langle \bar{B}\bar{B}\bar{B}BBB \rangle$$
$$\langle \bar{B}\bar{B}B\bar{B}BB \rangle$$
$$\langle \bar{B}\bar{B}BB\bar{B}B \rangle$$
$$\langle \bar{B}B\bar{B}B\bar{B}B \rangle$$
$$\langle \bar{B}\bar{B}\bar{B}B \rangle \langle BB \rangle \pm \langle \bar{B}\bar{B} \rangle \langle \bar{B}BBB \rangle$$
$$\langle \bar{B}\bar{B}BB \rangle \langle \bar{B}B \rangle$$
$$\langle \bar{B}B\bar{B}B \rangle \langle \bar{B}B \rangle$$
$$\langle \bar{B}\bar{B}\bar{B} \rangle \langle BBB \rangle$$
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$$\langle \bar{B}\bar{B} \rangle \langle \bar{B}B \rangle \langle BB \rangle$$
$$\langle \bar{B}B \rangle \langle \bar{B}B \rangle \langle \bar{B}B \rangle$$

$\langle \ldots \rangle$: flavor trace

Preliminary results for three baryon contact terms

- contact term of NNN reproduced: $V_{\mathrm{ct}}^{\mathrm{3NF}} = E\,\frac{1}{2}\sum_{i\neq j}\vec{\tau}_i\cdot\vec{\tau}_j$
- contact terms in different strangeness sectors:

strangeness	parameters
0	1 parameter
-1	additional 7 parameters
-2	additional 9 parameters
-3	additional 1 parameters
-4	no additional parameters
-5	no additional parameters
-6	no additional parameters

$\Rightarrow$ in total 18 parameters

ΛNN interaction

Isospin $I=0$: $V_{\Lambda NN\to\Lambda NN}^{I=0} = c_2\,\mathbb{1} + c_3\,\vec{\sigma}_1\cdot\vec{\sigma}_2 + c_3\,\vec{\sigma}_1\cdot\vec{\sigma}_3 + \frac{1}{3}c_2\,\vec{\sigma}_2\cdot\vec{\sigma}_3$

Isospin $I=1$: $V_{\Lambda NN\to\Lambda NN}^{I=1} = c_4(\mathbb{1} - \vec{\sigma}_2\cdot\vec{\sigma}_3)$

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Summary

- SU(3) chiral effective field theory for hyperon-nucleon potentials
- NLO analysis of one- and two-meson exchange and contact terms with SU(3) symmetric LECs [Nucl.Phys. A915, 2013]
- good description of available YN data;
comparable to phenomenological models
- complete classification of NLO baryon-baryon contact Lagrangian including external fields available [Nucl.Phys. A916, 2013]
- SU(3) classification of leading order three-baryon contact terms

Outlook

- include two-meson exchange with intermediate *decuplet* baryons
- include *explicit* SU(3) symmetry breaking in contact terms
- future applications: hypernuclei, exotic neutron star matter, hyperons in nuclear matter (Σ, Λ mean-fields)
- estimate strength of three-baryon forces