ηN and $\eta' N$ treatment within meson-baryon coupled channels

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Outline:

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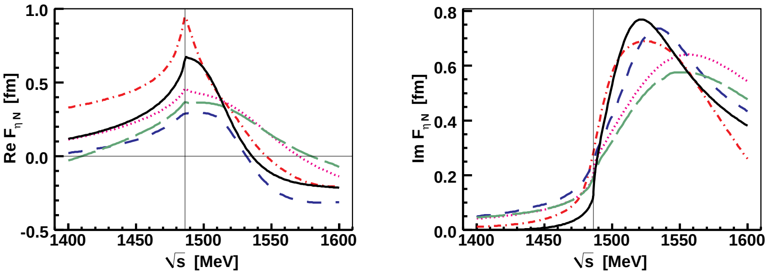
2. Chiral *MN* interactions with η_0-η_8 mixing
3. Fits to experimental data
4. ηN and $\eta' N$ amplitudes
5. Dynamically generated resonances (just briefly)
6. Summary

Based on: P.C. Bruns, A. C. - Nucl. Phys. A992 (2019) 121630

Motivation

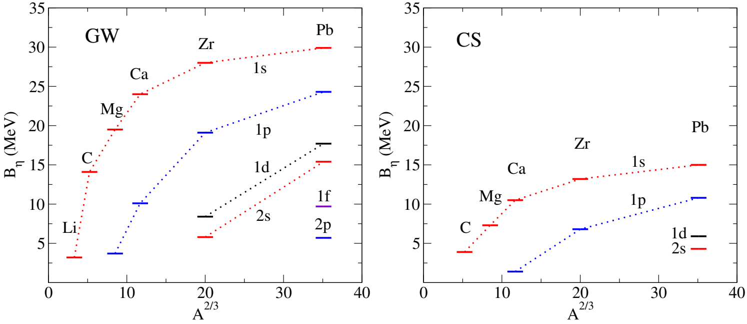
- The ηN and $\eta' N$ interactions are not sufficiently explored at energies close to threshold. For both systems, the analysis of available experimental data provides real part of the scattering length compatible with zero.
- The K-matrix and chirally motivated coupled channels approaches lead to theoretical predictions ranging from a moderate to reasonably strong attraction with $\text{Re}\, a_{\eta N} \approx 0.3 - 1.0$ fm. The $\eta' N$ theoretical predictions are more varied and much more dependent on the adopted model.
- The η and η' effective mass is reduced in nuclear medium relating to self-energies corresponding to attractive optical potentials, $V_{\rm opt} \sim t_{\eta N}\, \rho$
- Self-consistent calculations of η-nuclear quasi-bound states: $\text{Re}\, a_{\eta N} \gtrsim 0.7$ fm required to bind η in $A \gtrsim 12$ nuclei
  A.C., E. Friedman, A. Gal, J. Mares - Nucl. Phys. A925 (2014) 126

ηN amplitude (various models)



line	$a_{\eta N}$ [fm]	model
dotted	0.46+i0.24	*N. Kaiser, P.B. Siegel, W. Weise, PLB 362 (1995) 23*
short-dashed	0.26+i0.25	*T. Inoue, E. Oset, NPA 710 (2002) 354*
dot-dashed	0.96+i0.26	*A.M. Green, S. Wycech, PRC 71 (2005) 014001*
long-dashed	0.38+i0.20	*M. Mai, P.C. Bruns, U.-G. Meißner, PRD 86 (2012) 094033*
continuous	0.67+i0.20	*A.C., J. Smejkal, NPA 919 (2013) 46*

η-nuclear bound states predictions



- What is the impact of $\eta - \eta'$ mixing? How does it affect the ηN predictions.
- What can we say about the $\eta' N$ interaction.
- Will we observe η-nuclear or η'-nuclear bound states?

Chirally motivated $\eta N/\eta' N$ interactions

Coupled channels model based on chiral dynamics including the $\eta_0 - \eta_8$ mixing
P.C. Bruns, A. C. - Nucl. Phys. A992 (2019) 121630

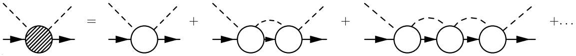
Involved channels: πN, ηN, $K\Lambda$, $K\Sigma$, $\eta' N$ ($I = 1/2$ sector)
πN, $K\Sigma$ ($I = 3/2$ sector)

Model features:

- only pseudoscalar meson - baryon channels considered, no $\pi\pi N$
- very large interval of energies $\sim 1.2 - 2.0$ GeV
- s-wave treatment sufficient for ηN and $\eta' N$ channels at energies close to the respective thresholds
- $N^*(1535)$ resonance about 40 MeV above the ηN threshold to be generated dynamically; the role of $N^*(1650)$ and $N^*(1895)$?

Problem: perturbation series do not converge in the vinicity of resonances!
Solution: construct effective potentials, then use Lippmann-Schwinger (or Bethe-Salpeter) equation to sum the major part of the perturbation series

$$T = V + V\ G\ T$$



Effective chiral Lagrangian

$$\mathcal{L}^{(1)}_{MB} = i\langle \bar{B}\gamma_\mu [D^\mu, B]\rangle - M_0\langle \bar{B}B\rangle + i\frac{w_s}{F_0^2}\eta_0^2\left(\langle [D^\mu,\bar{B}]\gamma_\mu B\rangle - \langle \bar{B}\gamma_\mu [D^\mu, B]\rangle\right)$$
$$+ \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle + \frac{1}{2}D_s\langle \bar{B}\gamma_\mu\gamma_5 B\rangle\langle u^\mu\rangle$$

two extra terms due to inclusion of the η_0 field:

- η_0 - baryon contact term proportional to w_s
- η_0 - baryon axial coupling term proportional to D_s

$$\mathcal{L}^{(2)}_{MB} = b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle$$
$$+ d_1\langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle + d_2\langle \bar{B}[u_\mu, [u^\mu, B]]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u_\mu u^\mu\rangle$$
$$+ (\text{some more } c_{D,F,0} \text{ and } d_{5,6,7} \text{ terms})$$

$$c_{D,F,0} = d_{5,6,7} = 0$$

one-mixing-angle scheme ($\vartheta = -15.5^\circ$) to describe the singlet-octet mixing:

$$\eta_8 = \eta\cos\vartheta + \eta'\sin\vartheta\,, \quad \eta_0 = \eta'\cos\vartheta - \eta\sin\vartheta$$

Separable meson-baryon potentials

$$V_{ij}(k,k';\sqrt{s}) = g_i(k^2)\, v_{ij}(\sqrt{s})\, g_j(k'^2)$$

$$v_{ij}(\sqrt{s}) = f_{0+,\mathrm{tree}}(s) = \frac{\sqrt{E_i+M_i}}{F_i}\left(\frac{C_{ij}(s)}{8\pi\sqrt{s}}\right)\frac{\sqrt{E_j+M_j}}{F_j}$$

- inter-channel energy dependent couplings C_{ij} determined by the SU(3) chiral Lagrangian
- Yamaguchi form factors $g_j(k) = 1/[1+(k/\alpha_j)^2]$ used to account naturally for the off-shell effects with inverse ranges α_j introduced as free model parameters

Lippmann-Schwinger equation used to solve exactly the loop series

$$f_{ij}(k,k';\sqrt{s}) = g_i(k^2)\left[(1 - v\cdot G(\sqrt{s}))^{-1}\cdot v\right]_{ij} g_j(k'^2)$$

The loop function $G(\sqrt{s})$ is diagonal in the channel space and is regularized by the Yamaguchi form factors.

Model parameters

- Meson decay constants fixed at *physical values* $F_\pi = 92.4$ MeV, $F_K = 110.0$ MeV, $F_\eta = 118.8$ MeV, and assuming $F_{\eta'} = F_\eta$.
- The Born terms couplings $F = 0.46$ and $D = 0.80$ as extracted in analysis of hyperon decays.
- $b_D = 0.1\ \text{GeV}^{-1}$, about average value from various fits and estimates available in the literature. Unlike b_0 and b_F, the b_D coupling is not so sensitive to *renormalization* due to loop function contributions.
- D_s set to be from the interval $\langle -0.6, -0.2 \rangle$, motivated by fits of the η and η' photoproduction and electroproduction data and compatible with the estimates for the $g_{\eta' NN}$ coupling. After finding the χ^2 minimum the D_s value fine-tuned in the next step.
- 12 free parameters: w_s, b_F, b_0, d_{1-4} and 5 inverse ranges α_j
- w_s should be small
  $w_s = -0.013$ - η,η' photoproduction and electroproduction
  Borasoy, Marco, Wetzel - PRC 66 (2002) 055208
  $-0.015 < w_s < 0.045$ - $\eta' N$ model presented in
  Oset, Ramos - PLB 704 (2011) 334

Effective inelasticity treatment

our approach - only two-body meson-baryon channels considered
reality - other, in particular $\pi\pi N$ channels, contribute to the inelasticities reported in the SAID database at energies around ηN threshold

Effective treatment:
observation - the total inelastic cross section for the πN-induced reactions is by about 20% larger (at the peak energy) when compared with the experimental $\pi^- p \to \eta n$ cross section. Thus, one can effectively account for the missing inelasticity by introducing 1.2 factor,

$$\sigma(\pi^- p \to \eta n) = \frac{2}{3}\sigma_{I=1/2}(\pi N \to \eta N)/1.2$$

$$\epsilon_r(\sqrt{s}) := [1 - \eta^2_{\rm SAID}(\sqrt{s})]/[1 - \eta^2_{0+}(\sqrt{s})] \approx 1.2$$

works reasonably well in most part of the $N^*(1535)$ resonance region. One can do even better,

$$\epsilon_r^{\rm eff}(\sqrt{s}) = a/(\sqrt{s} - m_\eta - M_N) + b$$

to describe quite well the energy dependence of the ratio ϵ_r

Fits to experimental data

- πN amplitudes from SAID database (S_{11} and S_{31} partial waves)
- $\pi^- p \longrightarrow \eta n$, $K^0\Lambda$ and $\eta' n$ production cross sections

model A global fit with the $\pi\pi N$ channel effectively accounted for by enhancing the fitted ηN cross sections by an energy dependent factor $\epsilon_r^{\rm eff}$ adjusted to provide the πN inelasticities from the SAID database

model B global fit with an effective factor $\epsilon_r^{\rm eff} = 1.2$

model C low energy fit restricted to energies $\sqrt{s} \leq 1600$ MeV, no $\eta_0 - \eta_8$ mixing, the $\eta' N$ channel decoupled, and $\epsilon_r^{\rm eff} = 1.2$

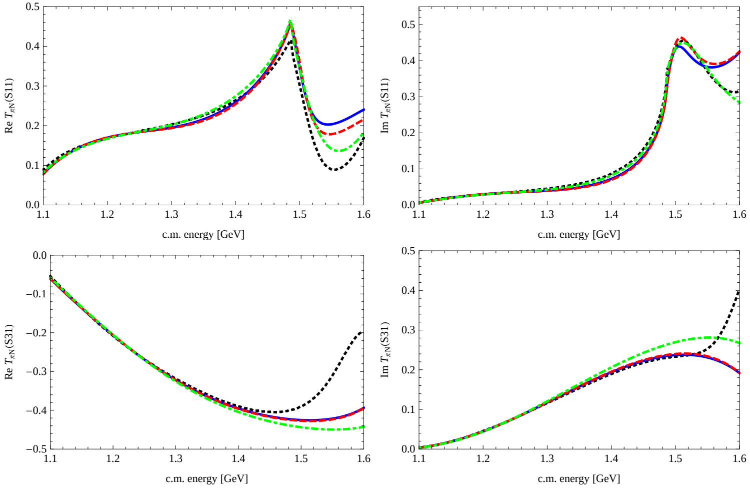
model D global fit with $\epsilon_r^{\rm eff} = 1$

model E global fit with $\epsilon_r^{\rm eff} = 1.2$ and the $\eta_0 - \eta_8$ mixing switched off

Fits to experimental data

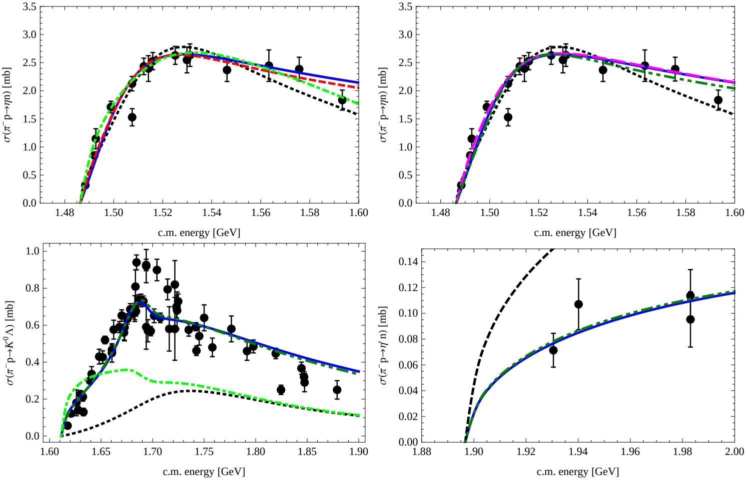
model	A	B	C	D	E
χ^2/dof	2.21	2.12	0.78	2.44	2.04
$\alpha_{\pi N}$	596	629	581	569	668
$\alpha_{\eta N}$	959	959	953	966	973
$\alpha_{K\Lambda}$	1188	1200	788	1172	1200
$\alpha_{K\Sigma}$	443	447	400	434	454
$\alpha_{\eta' N}$	911	916	—	923	1200
b_0	-0.452	-0.415	-0.673	-0.488	-0.368
b_F	-0.049	-0.028	0.184	-0.077	-0.002
d_1	-1.648	-1.643	0.630	-1.654	-1.638
d_2	0.574	0.569	0.161	0.572	0.696
d_3	1.190	1.263	3.547	1.115	1.252
d_4	-0.332	-0.329	-1.302	-0.336	-0.400
w_s	-0.038	0.011	—	-0.110	-0.236
D_s	-0.28	-0.27	—	-0.33	-0.29

πN amplitudes $T_{\pi N} = q_\pi \, f_{\pi N,\pi N}$



model A (continuous), model B (dashed), model C (dot-dashed), SAID (dotted)

$\pi^- p$ reaction cross sections



model A (continuous), model C (dot-dashed), model D (long-dashed), model E (dot-dot-dashed), CS (dotted)

bottom: p-wave (dotted), $\eta_0 - \eta_8$ mixing off but no re-fit (dashed)

ηN and $\eta' N$ elastic amplitudes

S_{11} scattering lengths (in fm) generated by our models:

model	A	B	C	D	E
πN	(0.20, 0.00)	(0.20, 0.00)	(0.22, 0.00)	(0.21, 0.00)	(0.20, 0.00)
ηN	(1.05, 0.17)	(0.86, 0.13)	(0.73, 0.26)	(1.10, 0.12)	(0.85, 0.09)
$\eta' N$	(-0.41, 0.04)	(-0.41, 0.04)	—	(-0.41, 0.04)	(-0.29, 0.04)

ηN unitarity constraint from the analysis of experimental $\pi N \to \eta N$ cross sections - $\mathrm{Im}\, a_{\eta N} > 0.172 \pm 0.009$ fm - models A and C comply

model C is compatible with earlier analyses
$a_{\eta N} = (0.67 + \mathrm{i}\,0.20)$ fm - A.C., Smejkal - NPA 919 (2013) 46
$a_{\eta N} = (0.77 + \mathrm{i}\,0.22)$ fm - Nieves, Ruiz Arriola - PRD 64 (2001) 116008

the η_0 component increases the ηN attraction to $\mathrm{Re}\, a_{\eta N} \approx 1$ fm in agreement with the phenomenological K-matrix analysis by Green and Wycech and prediction made by Bass and Thomas - PLB 634 (2006) 368.
good news for the η-nuclear states!

ηN and $\eta' N$ elastic amplitudes

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$\eta' N$	(-0.41, 0.04)	(-0.41, 0.04)	—	(-0.41, 0.04)	(-0.29, 0.04)

$\eta' N$ analysis of the $pp \longrightarrow pp\eta'$ reaction measurement at COSY provides

$$\text{Re}\, a_{\eta' N} = 0 \pm 0.43 \text{ fm and } \text{Im}\, a_{\eta' N} = 0.37^{+0.40}_{-0.16} \text{ fm}$$

Czerwinski et al. - PRL 113 (2014) 062004

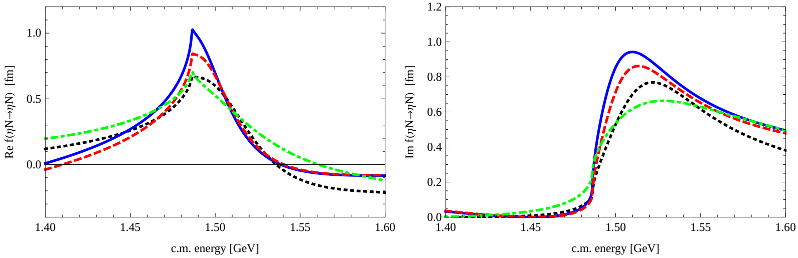
our $a_{\eta' N}$ predictions are remarkably stable, real part within the experimental limits, imaginary part too small due to model deficiencies

our models predict repulsive $\eta' N$ interaction at the threshold

bad news for the η'-nuclear states!

maybe too early to conclude due to our model limitations

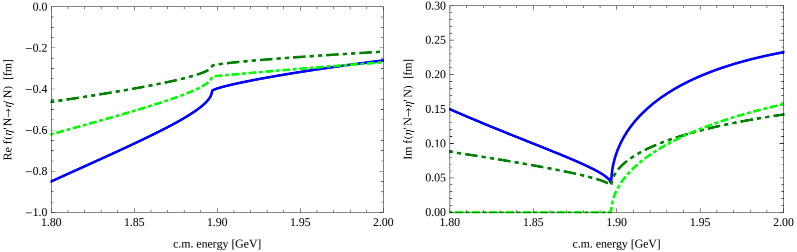
ηN elastic amplitude



model A (continuous), model B (dashed), model C (dot-dashed), CS model (dotted)

- Around threshold the ηN amplitude is clearly dominated by the $N^*(1535)$ resonance.
- The difference between our C model (fitted to low energy data) and the CS model is due to different treatment of the ηn cross sections data.
- Different $\pi\pi N$ inelasticity settings adopted in our models lead to moderate variations of the ηN amplitude energy dependence.

$\eta' N$ elastic amplitude



model A (continuous), model C (dot-dashed), model E (dot-dot-dashed)

- B and D models predictions coincide with those of model A and would overlap with the A model curves. $\pi\pi N$ inelasticity treatment has no impact on the $\eta' N$ amplitude.
- E model amplitude differs from the one generated by the A model despite both models providing practically the same $\eta' n$ cross sections
- All our models predict negative real part of the $\eta' N$ amplitude in the whole energy region. Most of this repulsion is caused by large NLO d-terms with the (negative) w_s term compensating partly to provide the $\eta' N$ scattering length appropriate to the fitted cross sections.

$\eta' N$ elastic amplitude

Should the $\eta' N$ interaction be attractive?

No direct evidence but there are some indications:

- η' effective mass shift in nuclear medium deduced from the photoproduction experiments on nuclear targets.
  Nanova et al. (CBELSA/TAPS) - PRC 94 (2016) 025205
- Similar in-medium mass shifts were also predicted in theoretical calculations based on the Nambu-Jona-Lasinio model and on the linear sigma model.
  Nagahiro, Takizawa, Hirenzaki - PRC 74 (2006) 045203
  Sakai, Jido - PRC 88 (2013) 064906
- $\eta' N$ coupling to $N^*(1895)$, almost at the $\eta' N$ threshold, should make the interaction attractive. A model by Oset and Ramos generates a resonance dynamically due to vector meson - baryon channels.
  Oset, Ramos - PLB 704 (2011) 334

Dynamically generated resonances

very brief account:

$N^*(1535)$ generated dynamically with a strong coupling to $K\Lambda$, satisfactory attributes when compared with PDG listings

$N^*(1650)$ generated dynamically with a strong coupling to $K\Sigma$, quite off the position listed in PDG as it is not restricted by the data used in our fits

$N^*(1895)$ missing in our approach; though, there is a pole coupling strongly to the $\eta' N$ channel ($\eta' N$ bound state with inter-channel couplings switched off) but drifting too far from being physically meaningful

look for more in our paper or ask us here ...

Summary

- Our chirally motivated coupled channels model does surprisingly well to reproduce the πN amplitudes and available cross sections data in a very large interval of energies, from the πN threshold to about 2 GeV.
- An explicit inclusion of the singlet meson field η_0 leads to more attractive ηN interaction at energies close to the channel threshold, a feature quite relevant for theoretical predictions and possible observation of the η-nuclear bound states.
- Our models predict a repulsive $\eta' N$ interaction in a broad interval of energies around the channel threshold.
- The $N^*(1535)$ and $N^*(1650)$ resonances are generated dynamically within our coupled-channel approach with strong couplings to the $K\Lambda$ and $K\Sigma$ channels, respectively.
- One should seriously consider adding other channels such as the $\pi\pi N$ one, vector-baryon channels, or couplings to some relevant resonant states not generated dynamically within the present approach.

Thanks to my collaborators !!!
P. Bruns, Řež (and J. Smejkal, Prague)