ηN interactions in the nuclear medium and η-nuclear bound states

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PLB 725 (2013) 334; NPA 925 (2014) 126; PLB 747 (2015) 345

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η *nuclei - status*

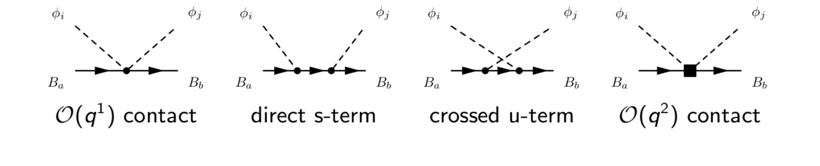
- Haider, Liu (PLB 172 (1986) 257, PRC 34 (1986) 1845)
  moderate attractive ηN interaction with scattering length $a_{\eta N} \sim 0.27 + i0.22$ fm $\Rightarrow \exists$ of η nuclear bound states (starting ^{12}C)
- Numerous studies since then yielding Re$a_{\eta N}$ from 0.2 fm to 1 fm
  chiral coupled channel models - Re$a_{\eta N} < 0.3$ fm;
  K matrix methods fitting πN and γN reaction data in the $N^*(1535)$ resonance region - Re$a_{\eta N} \sim 1$ fm $\rightarrow$ bound states already in He isotopes
- Strong final-state interaction have been noted in $p-$ and d-initiated η production (COSY-ANKE, COSY-GEM, LNS-SPES2,3,4)
- $^{25}_{\eta}Mg$? (COSY-GEM, PRC 79 (2009) 012201(R))
  $p +^{27}\mathrm{Al} \rightarrow^{25}_{\eta}\mathrm{Mg} +^{3}\mathrm{He};\quad {}^{25}_{\eta}\mathrm{Mg} \rightarrow (\pi^- + p) + X$
  $B_\eta = 13.1 \pm 1.6$ MeV and $\Gamma_\eta = 10.2 \pm 3.0$ MeV.
- But NO decisive experimental evidence so far.
  (negative results for $^{3}_{\eta}$He (photoproduction on ^{3}He - MAMI, PLB 709 (2012) 21.)
  and for $^4\eta$He ($dd \rightarrow ^3$He$p\pi^-$ - WASA@COSY PRC 87 (2013)035204.)

ηN *interactions*

- chiral SU(3)$_L$ $\times$SU(3)$_R$ meson-baryon effective Lagrangian for $\{\pi, K, \eta\} + \{N, \Lambda, \Sigma, \Xi\}$
- $\exists$ resonances $\Rightarrow \chi$PT not applicable $\rightarrow$
- nonperturbative coupled-channel resummation techniques

$$T_{ij} = V_{ij} + V_{ik} G_{kl} T_{lj}, \quad V_{ij} \text{ derived from } \mathcal{L}_\chi$$

Effective potentials are constructed to match the chiral meson-baryon amlitudes (up to NLO order)

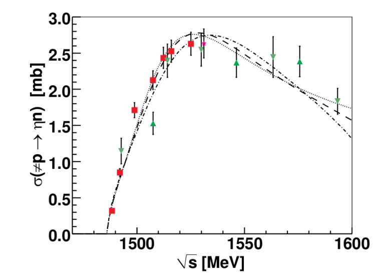


ηN *interactions*

- Channels involved:
  πN, ηN, $K\Lambda$, $K\Sigma$

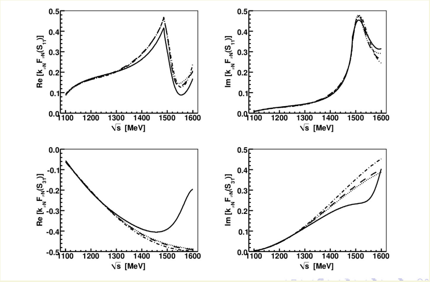
- Model parameters fixed by fitting low-energy meson-nucleon data:

$\pi N \rightarrow \eta N$ production X-section:



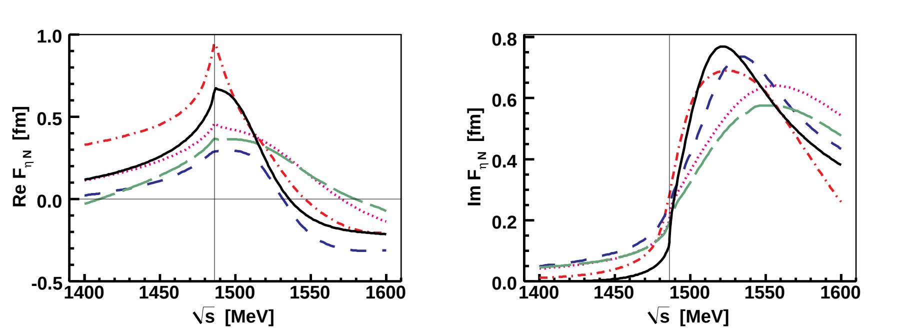
πN amplitudes from SAID database:

(S_{11} and S_{31} partial waves)



ηN scattering amplitudes

- ηN amplitudes for various models differ considerably
- Strong energy dependence of the scattering amplitudes !



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 (GR)*
dot-dashed	0.96+i0.26	*A.M. Green, S. Wycech, PRC 71 (2005) 014001 (GW)*
long-dashed	0.38+i0.20	*M. Mai, P.C. Bruns, U.-G. Meißner, PRD 86 (2012) 094033 (M2)*
full	0.67+i0.20	*A. Cieply, J. Smejkal, Nucl. Phys. A 919 (2013) 334 (CS)*

η in few-body systems

Variational calculation in hypersherical basis:

N. Barnea, E. Friedman, A. Gal, PLB 747 (2015) 345

2-body interactions

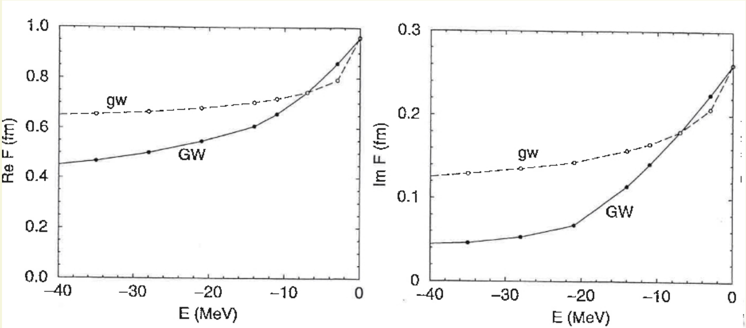
- NN: Argonne AV4' potential, Minnesota MN (central) potential
- ηN: complex energy-dependent local potential derived from the full chiral coupled-channels model:

  $$v_{\eta N}(E,r) = -\frac{4\pi}{2\mu_{\eta N}} b(E) \rho_\Lambda(r),$$

  where $E = \sqrt{s} - \sqrt{s_{\rm th}}$, $\rho_\Lambda(r) = (\frac{\Lambda}{2\sqrt{\pi}})^3 exp\left(-\frac{\Lambda^2 r^2}{4}\right)$

  $b(E)$ fitted to phase shifts δ derived from $F_{\eta N}(E)$ in GW and CS models

- Energy dependence of $b(E)$



$F_{\eta N}(E)$ generated from $v_{\eta N}(E)$ (GW), compared with the amplitude generated from $v_{\eta N}(E = 0)$ (gw).

Energy dependence of $v_{\eta N}(\sqrt{s})$

- A nucleons + η meson:

  $$s = (\sqrt{s_{\rm th}} - B_\eta - B_N)^2 - (\vec{p_\eta} + \vec{p_N})^2 \leq s_{\rm th}$$

  where $\sqrt{s_{\rm th}} = m_N + m_\eta$

- near threshold approximated by:

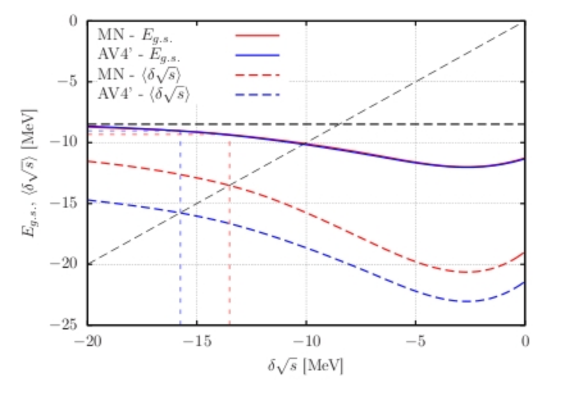
  $$\sqrt{s} = \sqrt{s_{\rm th}} + \delta\sqrt{s}, \quad \delta\sqrt{s} < 0!$$

  $$\langle \delta\sqrt{s} \rangle = -\frac{B}{A} - \frac{A-1}{A} B_\eta - \xi_N \frac{A-1}{A} \langle T_{N:N} \rangle - \xi_\eta \left(\frac{A-1}{A}\right)^2 \langle T_\eta \rangle,$$

  where B = total binding energy, $\xi_{N(\eta)} = m_{N(\eta)}/(m_N + m_\eta)$,
  $T_\eta = \eta$ kin. energy, $T_{N:N}$ = pairwise NN kin. energy

- $\langle \delta\sqrt{s} \rangle \Rightarrow$ selfconsistency

- Energy dependence $\Rightarrow$ selfconsistency



The ηNNN g.s. energy $E_{\text{g.s.}}$ (solid curves) + $\delta\sqrt{s}$ (dashed curves)

η in 3- and 4-body systems

- Conversion widths Γ of η nuclear few-body systems

  perturbative estimate: $\Gamma = -2\langle\Psi_{\mathrm{gs}}|\mathrm{Im}\,V_{\eta N}|\Psi_{\mathrm{gs}}\rangle$

- ηNN – NO bound state
- ηNNN – bound state ?

NN int.	$E(NNN)$	$E_{\mathrm{gs}}^{\mathrm{no\ sc}}$	$E_{\eta}^{\mathrm{no\ sc}}$	$\delta\sqrt{s_{\mathrm{sc}}}$	$E_{\mathrm{gs}}^{\mathrm{sc}}$	E_{η}^{sc}	$\Gamma_{\mathrm{gs}}^{\mathrm{sc}}$
MN	-8.38	-11.26	2.88	-13.52	-9.33	-0.95	6.76
AV4'	-8.99	-11.33	2.34	-15.83	-9.03	-0.04	7.88

η in many-body systems

A. Cieply, E. Friedman, A. Gal, J. Mares, PLB 725 (2013) 334, NPA 925 (2014) 126

- K.-G. equation:

  $$\left[\omega_\eta^2 + \vec{\nabla}^2 - m_\eta^2 - \Pi_\eta(\omega_\eta, \rho)\right] \phi_\eta = 0$$

  complex energy $\omega_\eta = m_\eta - B_\eta - \mathrm{i}\Gamma_\eta/2$

- $\Pi_\eta(\omega_\eta, \rho) = 2\omega_\eta V_\eta = -4\pi \frac{\sqrt{s}}{E_N} F_{\eta N}(\sqrt{s}, \rho)\rho$

- η in a nucleus $\Rightarrow$ polarized (compressed) $\rho \longrightarrow \Pi_\eta(\rho)$
  $\Rightarrow$ selfconsistent solution

η in many-body systems

- Selfenergy operator

$$\Pi_\eta(\omega_\eta) = 2\,\omega_\eta V_\eta = -4\pi \frac{\sqrt{s}}{E_N} F_{\eta N}(\sqrt{s}, \rho)\,\rho$$

- $F_{\eta N} = \eta N$ scattering amplitude with **two-body argument:**

$$\sqrt{s}\ \ (s = (\omega_\eta + E_N)^2 - (\vec{p}_\eta + \vec{p}_N)^2)$$

- ηN c.m. frame $\rightarrow$ η–nucleus c.m. frame $\quad\Rightarrow \vec{p}_\eta + \vec{p}_N \neq 0$

$$\Rightarrow \sqrt{s} \approx m_\eta + m_N - B_\eta - B_N - \xi_N \frac{p_N^2}{2m_N} - \xi_\eta \frac{p_\eta^2}{2m_\eta} = E_{\rm th} + \delta\sqrt{s},$$

$$\delta\sqrt{s} = B_N \frac{\rho}{\bar{\rho}} - \xi_N B_\eta \frac{\rho}{\rho_0} - \xi_N T_N \left(\frac{\rho}{\rho_0}\right)^{2/3} + \xi_\eta {\rm Re}\, V_\eta(\sqrt{s}, \rho)$$

- $\rho =$ nucl. medium density (RMF calculations)

- $V_\eta, B_\eta \ \Rightarrow$ self-consistent solution

Free space amplitudes → in-medium amplitudes

- WRW method - T. Wass, M. Rho, W. Weise, NPA 617 (1997) 449.

$$F_{\eta N}(\sqrt{s},\rho) = \frac{F_{\eta N}(\sqrt{s})}{1+\xi(\rho)(\sqrt{s}/E_N)F_{\eta N}(\sqrt{s})\rho} \ ,$$

$$\xi(\rho) = \tfrac{9\pi}{4p_f^2} I(\kappa), \qquad I(\kappa) = 4\int_0^\infty \tfrac{dt}{t}\exp(iqt)j_1^2(t), \qquad \kappa = \tfrac{1}{p_f}\sqrt{2m_\eta(B_\eta + \mathrm{i}\Gamma/2)}.$$

- Chiral coupled-channels model - A. Cieply, J. Smejkal, NPA 919 (2013) 334.

  multi-channel L.-Sch. equation:

  $F = V + VGF$, F, V in separable form,

  $$G_n(\sqrt{s};\rho) = -4\pi \int_{\Omega_n(\rho)} \frac{d^3\vec{p}}{(2\pi)^3} \frac{g_n^2(p)}{k_n^2 - p^2 - \Pi_n(\sqrt{s},\vec{p};\rho) + i0} \ .$$

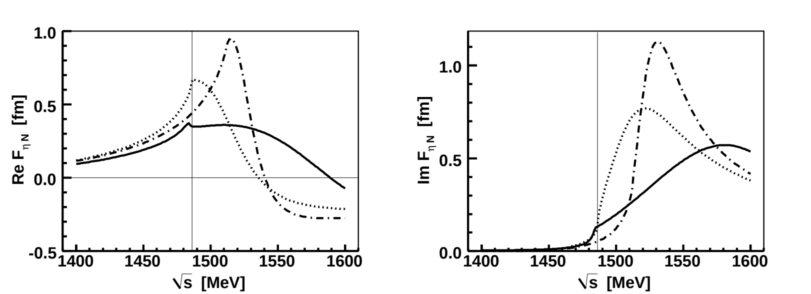
  $\Omega_n(\rho)$ → intermediate N energy is above Fermi level (Pauli blocking)

  Π → hadron **self-energies** in G (+SE option)

  ⇒ self-consistency

ηN scattering amplitudes

- Energy dependence of $f_{\eta N}(\sqrt{s})$



chiral CS model (A. Cieply, J. Smejkal, Nucl. Phys. A 919 (2013) 334)

dotted curve: free-space, dot-dashed: Pauli blocked, full: Pauli blocked + hadron selfenergies

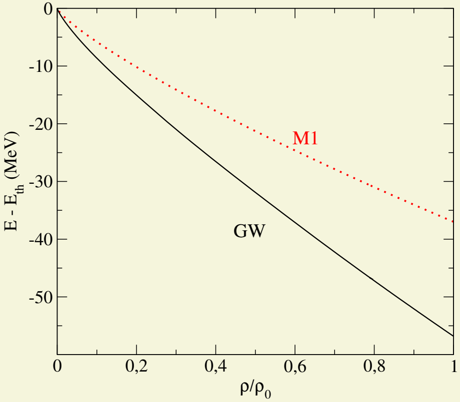
- Nuclear medium reduces the ηN attraction at threshold, the amplitude becomes smaller when going subthreshold

η nuclear states

Energy dependence of $V_\eta(\sqrt{s}) \longleftarrow$ due to $N^*(1535)$

- In-medium (subthreshold) energy shift:

$$\delta\sqrt{s} = -B_N \frac{\rho}{\bar{\rho}} - \xi_N B_\eta \frac{\rho}{\rho_0} - \xi_N T_N (\frac{\rho}{\rho_0})^{2/3} + \xi_\eta \mathrm{Re} V_\eta(\sqrt{s}, \rho)$$

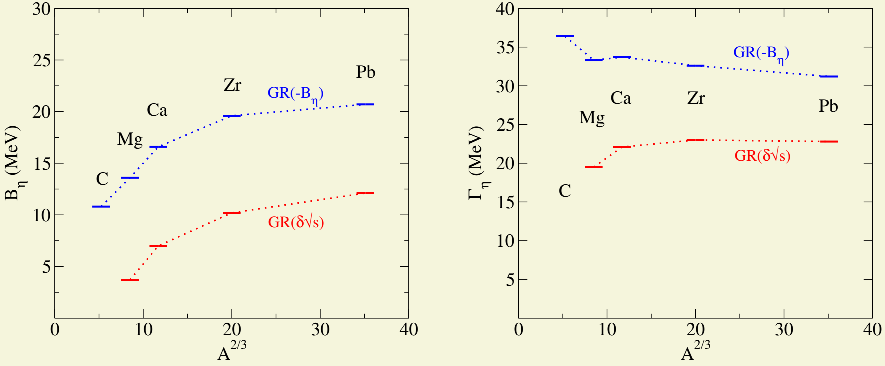


- B_η, V_η, $\rho \Rightarrow$ selfconsistent solution $\rightarrow$

40 - 60 MeV energy shift at ρ_0 – larger than shift by B_η (GR) or by 30 MeV (Haider, Liu)

η nuclear states

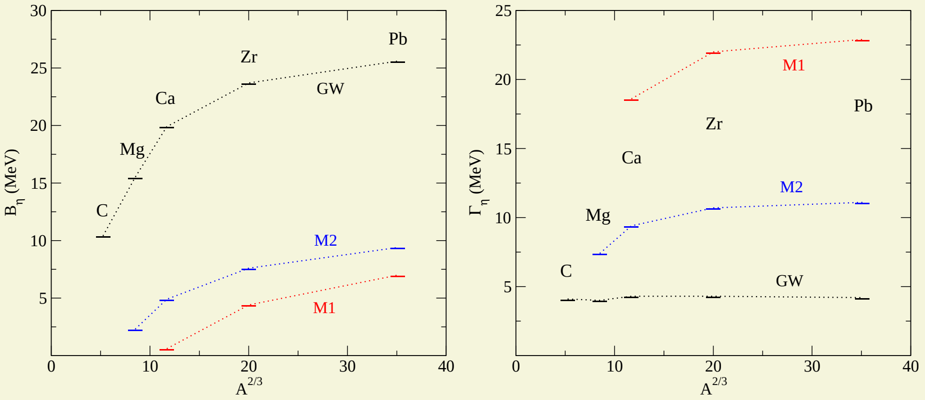
- Sensitivity to the energy shift:
  selfconsistent $\delta\sqrt{s}$ reduces both 1s B_η and Γ_η



- GR widths too large to resolve η bound states !

η nuclear states

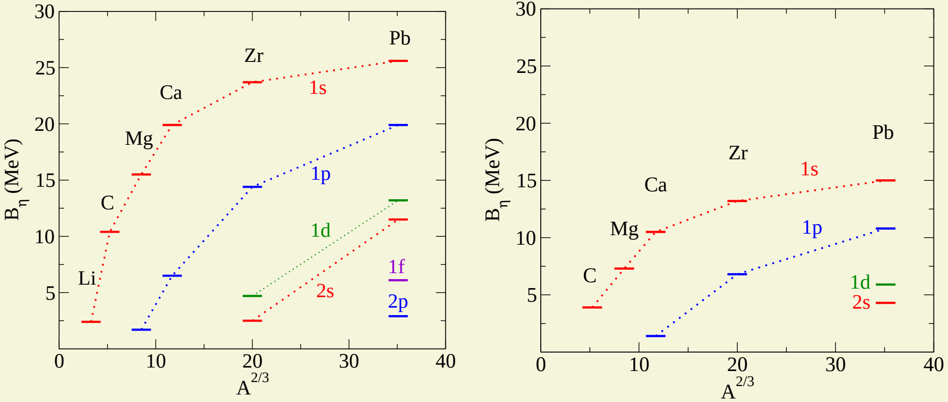
- Model dependence:



- Larger Re $a_{\eta N}$ gives larger B_η **vs.** no relation between Im $a_{\eta N}$ and Γ_η

η nuclear states

- Predictions of GW and CS models:
  all states in selected nuclei are shown; both models give small widths ($\Gamma_\eta < 5$ MeV)



Summary

- Large energy shift and rapid decrease of the ηN amplitudes lead to relatively small binding energies and widths of the calculated η nuclear bound states
- CS and GW models predict η nuclear states with small widths (< 5 MeV) $\rightarrow$ this might encourage further attempts to produce and identify η nuclear bound states.
- additional width contribution not considered in this work due to $\eta N \rightarrow \pi\pi N$ and $\eta NN \rightarrow NN \Rightarrow$ estimated to add few MeV
- Subthreshold behavior of $F_{\eta N}$ is crucial to decide whether η nuclear states exist, in which nuclei, and if their widths are small enough to be resolved in experiment.