η-mesic nuclei

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PLB 725 (2013) 334; NPA 925 (2014) 126; PLB 747 (2015) 345, PLB 771 (2017) 297

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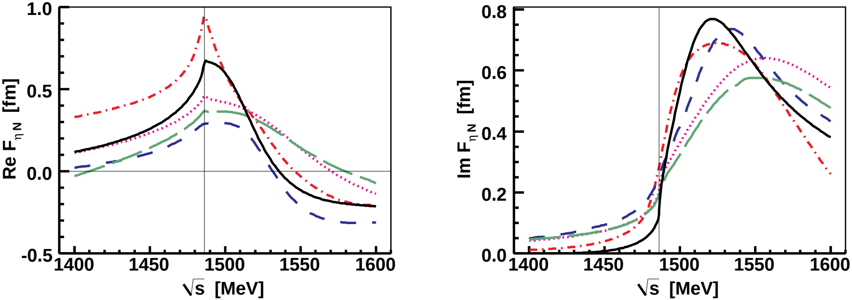
η nuclei - status

- 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;
  $pd \rightarrow \eta^3$He reaction - Xie, Liang, Oset, Moskal, Skurzok, Wilkin, PRC 95 (2017) 015202)
  and for $^{4}_{\eta}$He ($dd \rightarrow ^{3}\mathrm{He}N\pi$ - WASA@COSY PRC 87 (2013)035204; NPA 959 (2017) 102.)

ηN scattering amplitudes

- ηN amplitude for various models:
- 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

Faddeev (AGS) calculations of ηNNN and $\eta NNNN$ systems

A. Fix, O. Kolesnikov, PLB 772 (2017) 663

Variational calculations

- in hypersherical basis

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

- within Stochastic Variational Method (SVM)

  N. Barnea, E. Friedman, A. Gal, NPA 968 (2017) 35;

  N. Barnea, B. Bazak, E. Friedman, A. Gal, PLB 771 (2017) 297

interactions involved in variational calculations

- NN: Argonne AV4' potential, Minnesota MN 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 $E = \sqrt{s} - \sqrt{s_{\rm th}}$, $\quad \rho_\Lambda(r) = (\frac{\Lambda}{2\sqrt{\pi}})^3 exp\left(-\frac{\Lambda^2 r^2}{4}\right)$

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

  scale Λ inversely proportional to the $v_{\eta N}$ range

- π-less EFT at LO

  nuclear dynamics generated from two NN + one NNN contact terms (CT);

  one ηN + one ηNN CT (CT(ηNN) = CT(NNN) or CT(ηNN) fitted to $B_\eta(\eta NN) = 0$;

  $v_{\eta N}$ = regulated contact term in π-less EFT

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:

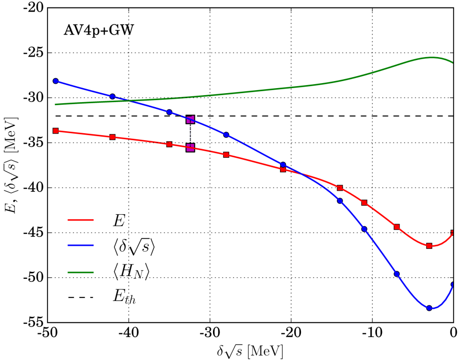
  $$\sqrt{s} = \sqrt{s_{\rm th}} + \delta\sqrt{s}, \quad \delta\sqrt{s} < 0!$$

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

  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 ${}^4_\eta$He g.s. energy $E + <\delta\sqrt{s}> + <H_N>$, for AV4 and GW potentials with $\Lambda = 4$ fm^{-1}

η in 3- and 4-body systems

- Conversion widths Γ of η nuclear few-body systems

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

Results:

- ηNN - unbound
- η^3He

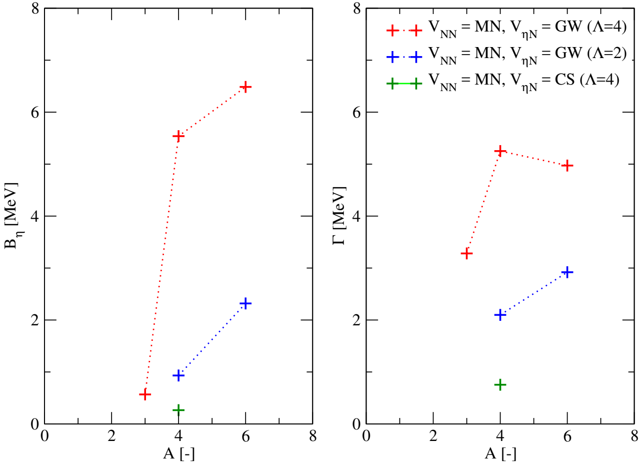
	NN int.	$\delta\sqrt{s_{sc}}$	B_η	Γ_{gs}
GW, $\Lambda = 2$	MN	-9.385	0.099	1.144
	AV4'	-11.478	-0.028	0.769
GW, $\Lambda = 4$	MN	-13.392	0.990	3.252
	AV4'	-14.881	0.686	2.438
CS, $\Lambda = 2$	MN	-8.388	-0.217	0.057
CS, $\Lambda = 4$	MN	-8.712	-0.161	0.227

- η^4He

	NN int.	$\delta\sqrt{s_{\rm sc}}$	B_η	$\Gamma_{\rm gs}$
GW, $\Lambda = 2$	MN	-19.477	0.96	1.975
	AV4'	-23.646	0.38	1.207
GW, $\Lambda = 4$	MN	-29.750	4.69	4.5
	AV4'	-32.411	3.51	3.615
CS, $\Lambda = 2$	MN	-16.704	-0.16	0.133
CS, $\Lambda = 4$	MN	-19.246	0.47	0.901

η in 3-, 4- and 6-body systems

- SVM for Minnesota NN model + GW and CS ηN models; no Coulomb
  calculated by M. Schaefer, preliminary (results from yesterday)!



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 $\Rightarrow \vec{p}_\eta + \vec{p}_N \neq 0$

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

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

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

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

Free space amplitudes → in-medium amplitudes

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

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

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

- 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,

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

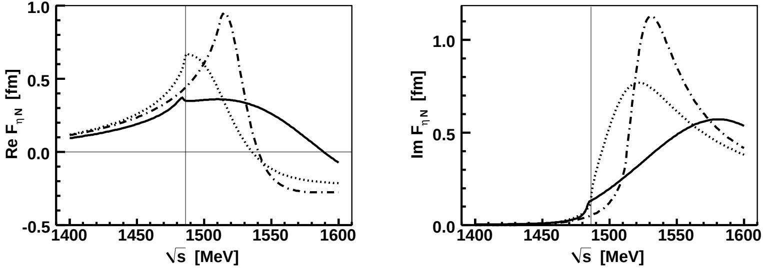
  $\Omega_n(\rho)$ → intermediate N energy is above Fermi level (Pauli blocking)

  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

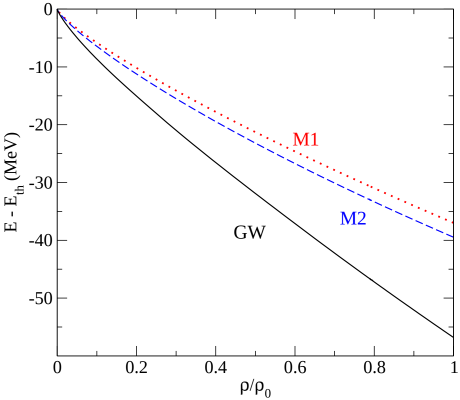
- Nuclear medium reduces the ηN attraction at threshold, the amplitude becomes smaller when going subthreshold

Energy shift

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

- In-medium (subthreshold) energy shift:

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

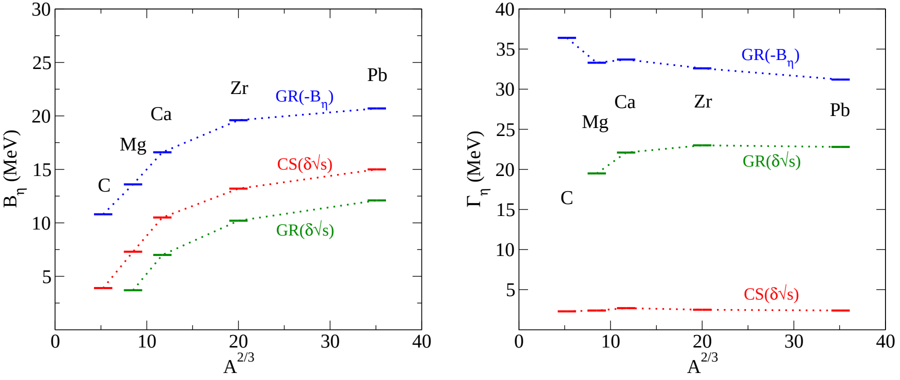


- B_η, V_η, $\rho \Rightarrow$ selfconsistent solution $\rightarrow$

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

η nuclear states

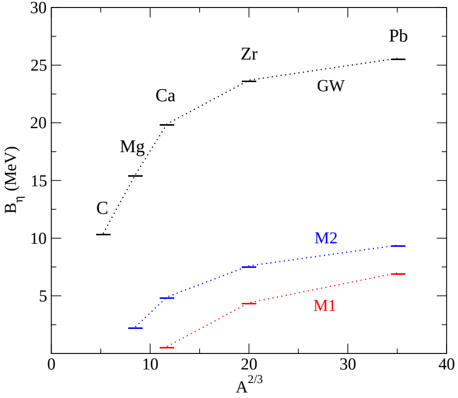
- Sensitivity to the energy shift:
  selfconsistent $\delta\sqrt{s}$ reduces both 1s B_η and Γ_η

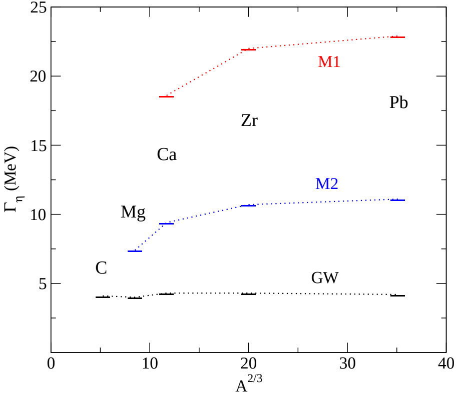


- GR widths too large to resolve η bound states !

η nuclear states

- Model dependence:

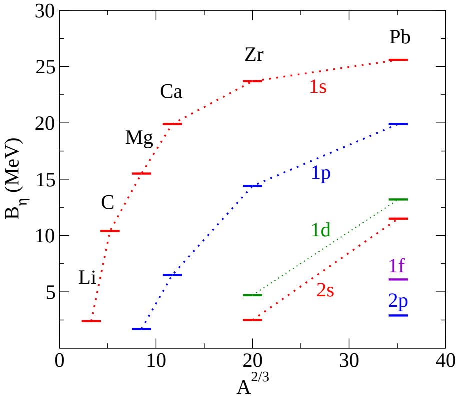


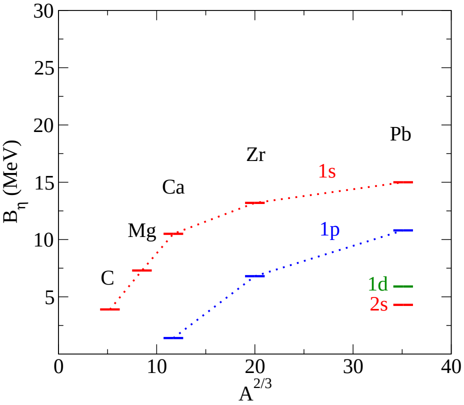


- Larger Re $a_{\eta N}$ gives larger B_η **vs.** no relation between Im $a_{\eta N}$ and Γ_η

η nuclear states

- Predictions of GW and CS models:
  all states in selected nuclei are shown; both models give small widths





Summary

η nuclear bound states:

- Large energy shift and rapid decrease of the ηN amplitudes below threshold $\Rightarrow$ relatively small binding energies and widths of the calculated η nuclear bound states

  ηd unbound in considered models

  $^{3}_{\eta}$He bound state $\leftarrow$ Re$a_{\eta N} \approx 1$ fm

  $^{4}_{\eta}$He bound state $\leftarrow$ Re$a_{\eta N} \geq 0.7$ fm

  $^{12}_{\eta}$C bound state $\leftarrow$ Re$a_{\eta N} \geq 0.5$ fm

- 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.

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