Energy and density dependence of the $\bar{\mathrm{K}}$N and ηN amplitudes near threshold

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collaboration with J. Smejkal on the meson-nucleon model

and with E. Friedman, A. Gal, D. Gazda, and J. Mareš on in-medium applications

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Outline

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- A.C., J. Smejkal - Nucl. Phys. A 881 (2012) 115
- A.C., J. Smejkal - Nucl. Phys. A 919 (2013) 46
- A.C., E. Friedman, A. Gal, D. Gazda, J. Mareš - PRC 84 (2011) 045206
- A.C., E. Friedman, A. Gal, J. Mareš, Nucl. Phys. A 925 (2014) 126

Introduction

$\bar{K}N$ and ηN interactions

strongly interacting multichannel system with an s-wave resonance near threshold
modern theoretical treatment based on an effective chiral Lagrangian

$\downarrow\downarrow\downarrow$

$\bar{K}NN$ coupled systems

? narrow measurable states
FINUDA, DISTO, OBELIX results
not quite understood, conflicting interpretations

kaonic deuterium atom

predictions for the SIDDHARTA-2 experiment

Fadeeev type and variational calculations

$\downarrow\downarrow\downarrow$

$\bar{K}/\eta$-nuclear interaction

$$V_{\rm opt}(\rho) \sim t_{MN}(\rho)\, \rho$$

? optical potential depth:

phenomenology $V^{\bar{K}}_{\rm opt}$=**(150-200)** MeV

chiral models $V^{\bar{K}}_{\rm opt}$=**(50-60)** MeV

? existence of sufficiently narrow K^-/η–nuclear bound states

related issue: **meson propagation in hot and dense nuclear matter**
heavy ion collisions, kaon condensation, neutron star structure

Introduction

very basic comparison of the $\bar{K}N$ and ηN systems

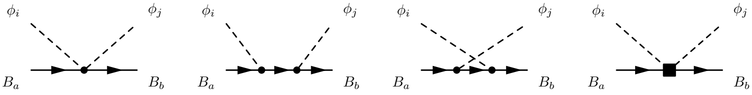
	E_{th} (MeV)	resonance	a_{MN} (fm)
$\bar{K}N$	1434	$\Lambda(1405)$	$-0.15 + 0.62\,\mathrm{i}$
ηN	1486	$N^*(1535)$	$0.67 + 0.20\,\mathrm{i}$

nuclear medium affects the strength of the meson-nucleon interaction which is to be evaluated at subthreshold energies when meson-nuclear states are studied

Separable meson-baryon potentials

We use effective separable potentials that match the chiral meson-baryon amplitudes up to NLO order *[Kaiser, Siegel and Weise (1995)]*

Schematic picture:



$\mathcal{O}(q^1)$ contact   direct s-term   crossed u-term $\mathcal{O}(q^2)$ contact

Parameters: f_π, f_K, f_η - meson decay constants

$D \simeq 3/4$, $F \simeq 1/2$ - axial vector couplings, $g_A = F + D$

b_0, b_D, b_F, four d's - second order couplings

M_0 - baryon octet mass

low energies around threshold - only s-wave considered

Separable meson-baryon potentials

$$V_{ij}(k,k';\sqrt{s}) = g_i(k^2)\, v_{ij}(\sqrt{s})\, g_j(k'^2)$$
$$v_{ij}(\sqrt{s}) = -\frac{C_{ij}(\sqrt{s})}{4\pi f_i f_j}\sqrt{\frac{M_i M_j}{s}}$$

- inter-channel couplings C_{ij} determined by the chiral SU(3) symmetry
- 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

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

where the Green function $G(\sqrt{s})$ is diagonal in the channel space and becomes density dependent in nuclear medium

Separable meson-baryon potentials

in the free space

$$G_n(\sqrt{s}) = -4\pi \int \frac{d^3p}{(2\pi)^3} \frac{g_n^2(p^2)}{k_n^2 - p^2 + \mathrm{i}0} = \frac{(\alpha_n + \mathrm{i}k_n)^2}{2\alpha_n} \left[g_n(k_n)\right]^2$$

nuclear medium treatment

$$G_n(\sqrt{s},\rho) = -4\pi \int_{\Omega_n(\rho)} \frac{d^3p}{(2\pi)^3} \frac{g_n^2(p^2)}{k_n^2 - p^2 - \Pi_n(\sqrt{s},p;\rho) + \mathrm{i}0}$$

- integration domain $\Omega_n(\rho)$ is limited by the Pauli principle in channels involving nucleons
- Π_n represents a sum of meson and baryon self-energies in channel n
- $\Pi_{\bar{K}} \sim F_{\bar{K}N}\,\rho$ or $\Pi_\eta \sim F_{\eta N}\,\rho \;\Rightarrow\;$ selfconsistent treatment required

Separable meson-baryon potentials

Involved channels: $\pi\Lambda$, $\pi\Sigma$, $\bar{K}N$, $\eta\Lambda$, $\eta\Sigma$, $K\Xi$ $(S=-1)$
πN, ηN, $K\Lambda$, $K\Sigma$ $(S=0)$

Model parameters (NLO d-couplings, inverse interaction ranges) fixed in fits to low energy meson-nucleon data.

$S=-1$ sector ($\bar{K}N$ related channels)

- kaonic hydrogen data (SIDDHARTA)
- $K^{-}p$ threshold branching ratios
- $K^{-}p$ low energy cross sections

$S=0$ sector (ηN related channels)

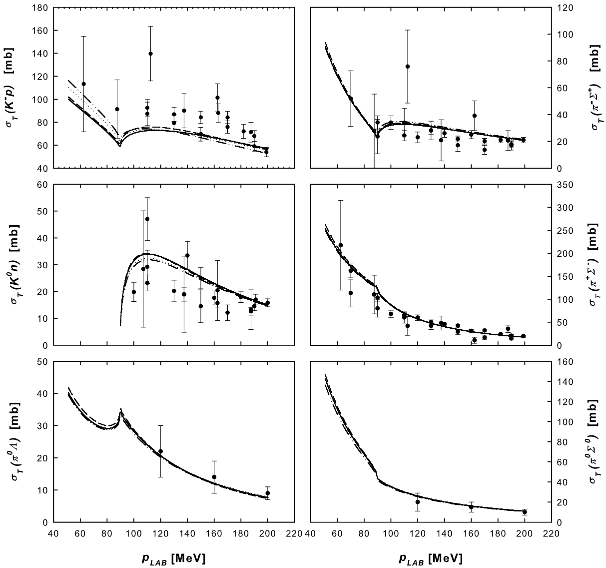
- πN amplitudes from SAID database (S_{11} and S_{31} partial waves)
- $\pi N \longrightarrow \eta N$ production cross sections

Results

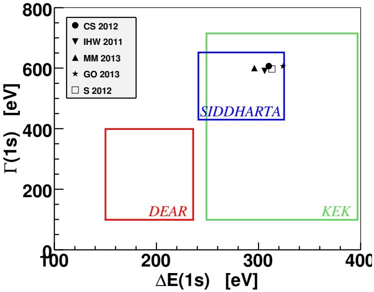
$\bar{K}N$ results

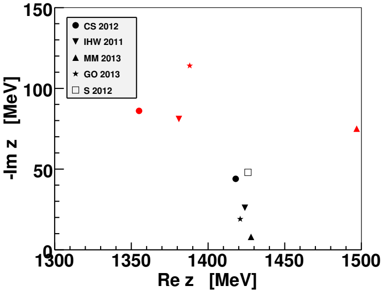
($S = -1$ sector)

K^-p reaction total cross sections



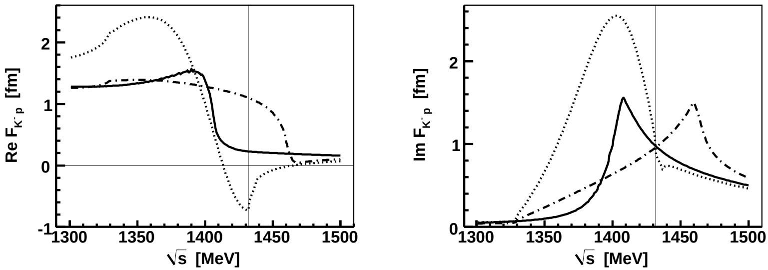
kaonic hydrogen 1s level characteristics and $\Lambda(1405)$ poles





- chiraly motivated models generate dynamically two $I = 0$ poles assigned to the $\Lambda(1405)$ resonance; origin of those poles - $\pi\Sigma$ resonance, $\bar{K}N$ bound state that are moved to their physical resonant positions due to strong $\pi\Sigma$-$\bar{K}N$ coupling
- all models tend to agree on the kaonic hydrogen characteristics and to some extend on the position of the $\bar{K}N$ related pole
- the data are not very sensitive to the position of the $\pi\Sigma$ related pole

$\bar{K}N$ amplitude (free and in medium)



dotted - in vacuum, dot-dashed - Pauli blocked, continuous - Pauli blocked + hadron selfenergies

- At the $\bar{K}N$ threshold in-medium Pauli blocking changes the K^-p free space repulsion into attraction and moves the resonance structure to higher energies. Hadron selfenergies move it back below the threshold.
- The in-medium (chiral) $\bar{K}N$ interaction is relatively weak (a shallow $\bar{K}$-nuclear optical potential) at threshold but becomes much stronger (a deep optical potential) when going subthreshold.

$\bar{K}$-nuclear optical potential

single nucleon approximation, a coherent sum of $\bar{K}N$ interactions:

$$V_{K^-}(\sqrt{s};\rho) = -\frac{2\pi}{\omega_K}\,(1+\frac{\omega_K}{m_N})\,F_{K^-N}(\sqrt{s};\rho)\,\rho$$

The kaons interacting with nuclei probe the subthreshold energy region!
two-body c.m. system: $\vec{p}_K + \vec{p}_N = \vec{0}$
K^-–nucleus c.m. system: $\vec{p}_K + \vec{p}_N \neq \vec{0}$

bound hadrons, averaging over angles, local density approximation, Fermi gas model:

$$\sqrt{s} \approx E_{\rm th} - B_N\frac{\rho}{\bar{\rho}} - \xi_N\,B_K\frac{\rho}{\rho_0} - \xi_N\,T_N(\frac{\rho}{\rho_0})^{2/3} + \xi_K\,{\rm Re}\,\mathcal{V}_{K^-}(\rho)$$

where $\xi_{N(K)} = m_{N(K)}/(m_N + m_K)$

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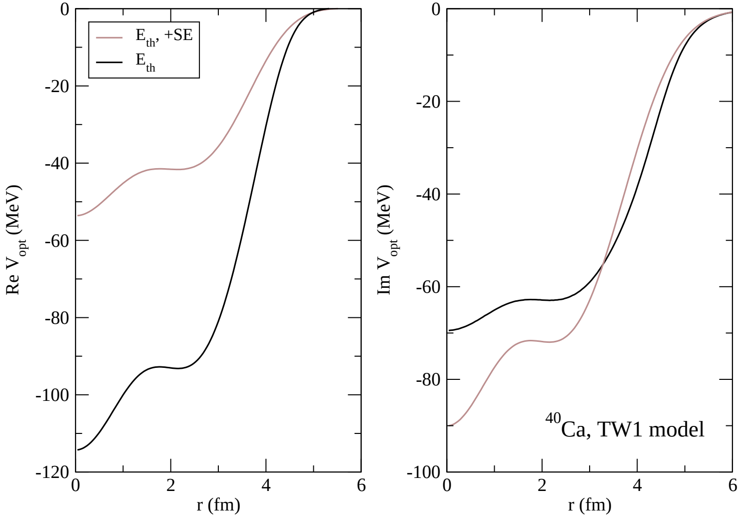
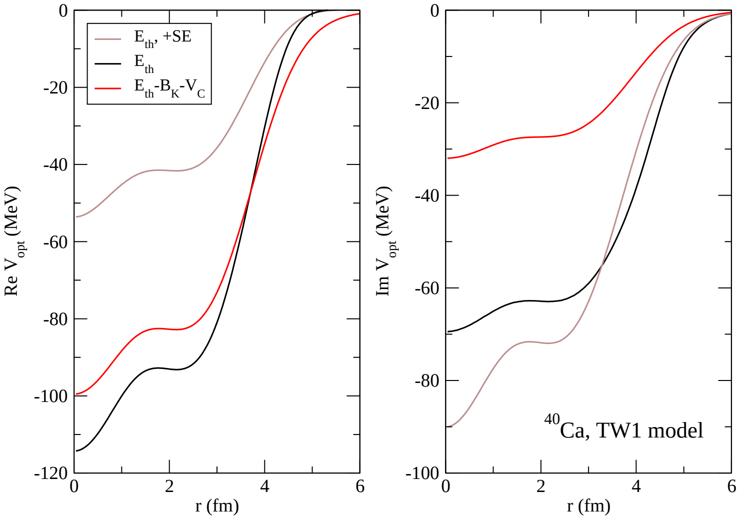
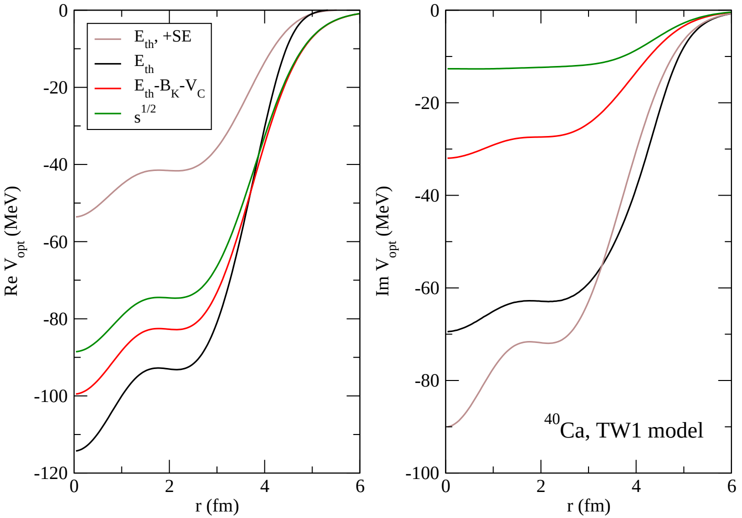
$\bar{K}$-nuclear optical potential



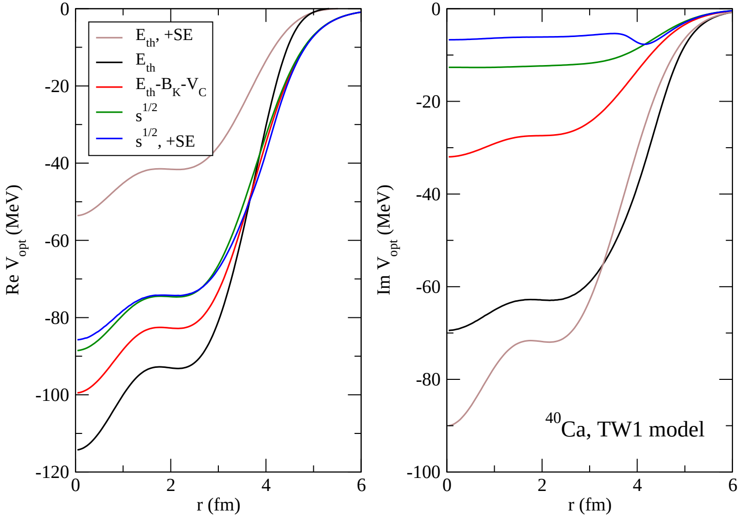
$\bar{K}$-nuclear optical potential



$\bar{K}$-nuclear optical potential

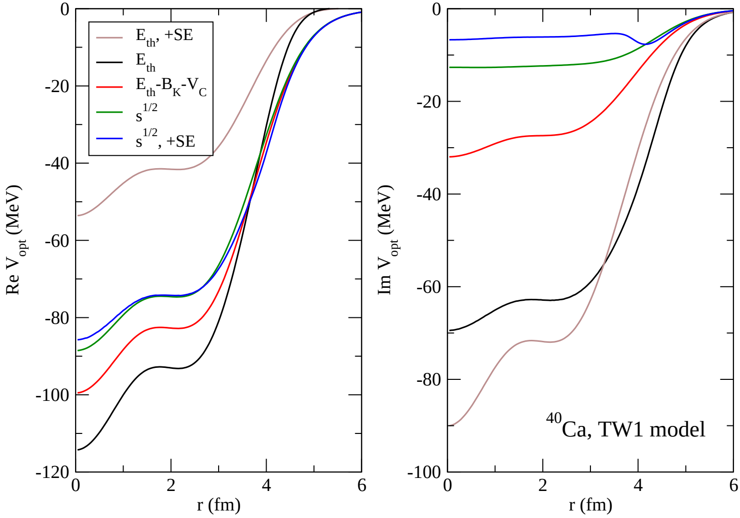


$\bar{K}$-nuclear optical potential



calculations by D. Gazda, J. Mareš, Nucl. Phys. A 881 (2012) 159

$\bar{K}$-nuclear optical potential



calculations by D. Gazda, J. Mareš, Nucl. Phys. A 881 (2012) 159

K^--nuclear quasi-bound states

TW1 vs. CS30 vs. NLO30 models

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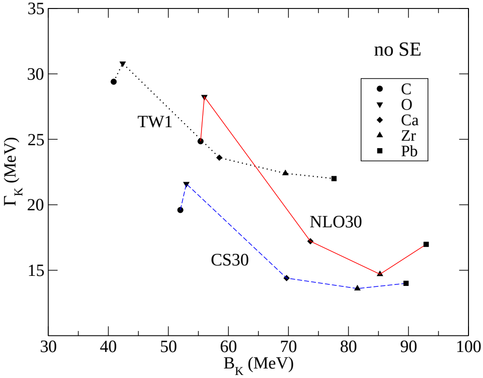


- B_{K^-} and Γ_{K^-} of 1s K^- nuclear states, calculated self-consistently using the in-medium 'noSE' amplitudes.
- no $\bar{K}NN \to YN$, no p-wave

Results

ηN results

($S = 0$ sector)

$S = 0$ fit results

4 inverse ranges α and 4 d-couplings fitted to

- πN partial waves S_{11} up to 1600 MeV (30 single energy data points)
- πN partial waves S_{31} up to 1450 MeV (21 single energy data points)
- $\pi N \longrightarrow \eta N$ total cross sections up to 1600 MeV (13 data points)

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

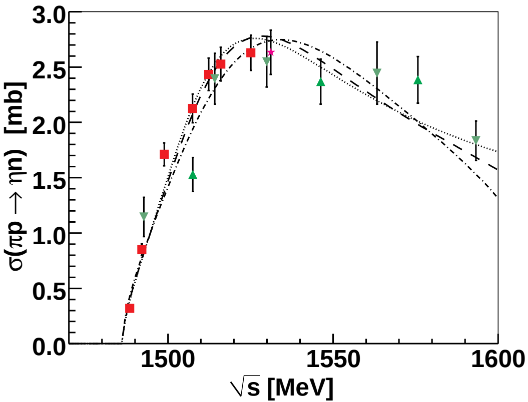
the 1.2 factor accounts effectively for a missing $\pi\pi N$ channel

model	χ^2/dof	$\alpha_{\pi N}$	$\alpha_{\eta N}$	$\alpha_{K\Lambda}$	$\alpha_{K\Sigma}$	d_D	d_F	d_0	d_1
NLO20$_\eta$	1.33	597	1293	256	1032	2.062	-0.896	-2.279	3.528
NLO30$_\eta$	1.46	538	1635	250	939	1.981	-0.770	-2.452	3.940
NLO40$_\eta$	1.95	508	2000	250	842	1.863	-0.685	-2.608	4.366
KSW	—	573	776	776	776	0.420	-0.410	-0.745	-0.380

$$\sigma_{\pi N} = -2m_\pi^2(2b_0 + b_D + b_F)$$

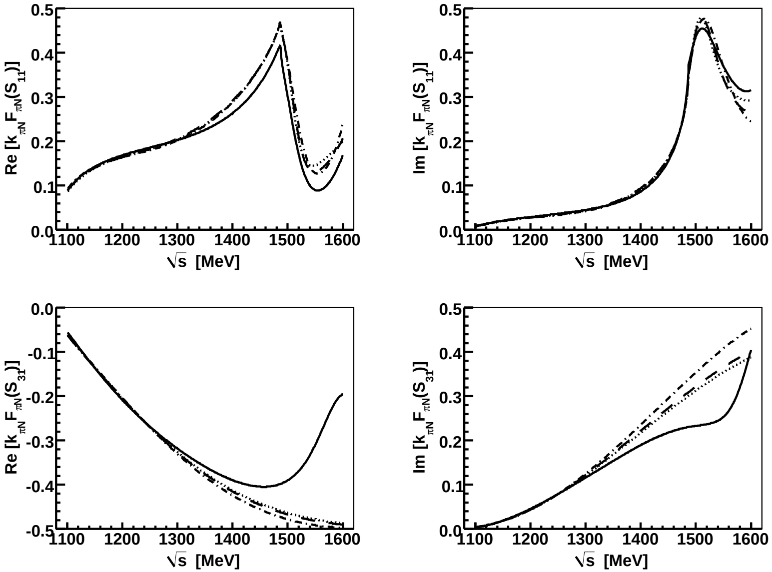
$$\chi^2/dof = \frac{\sum_i N_i}{N_{obs}(\sum_i N_i - N_{par})} \sum_i \frac{\chi_i^2}{N_i}$$

$S = 0$ results - ηN production

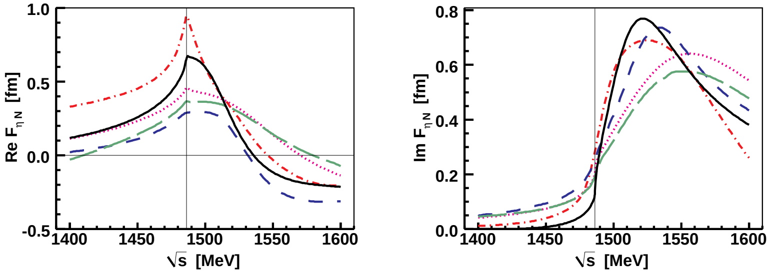


A comparison of the model predictions for the $\pi^- p \rightarrow \eta n$ total cross section. The results obtained with the NLO20$_\eta$ model (dotted line), NLO30$_\eta$ model (dashed line) and the NLO40$_\eta$ model (dot-dashed line), are plotted together with the experimental data.

$S = 0$ results - πN amplitudes

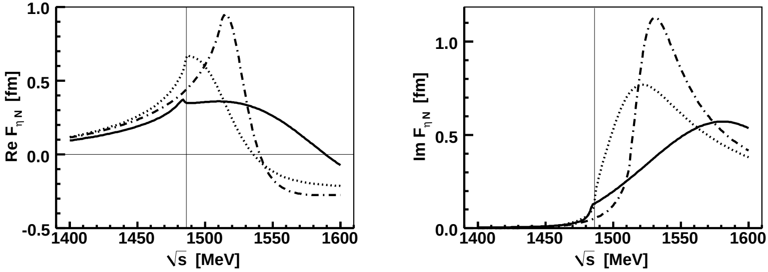


ηN amplitude (various models)



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*

ηN amplitude (free and in medium)

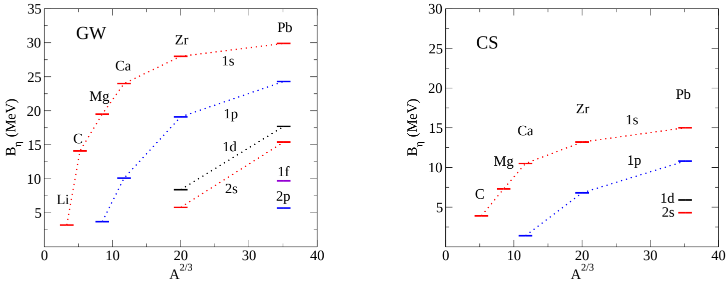


dotted - in vacuum, dot-dashed - Pauli blocked, continuous - Pauli blocked + hadron selfenergies

- The nuclear medium reduces the ηN attraction at threshold, though the impact on the energy dependence of the amplitude is small at subthreshold energies. Small Im $F_{\eta N}$ for $E < E_{th}$!
- $N^*(1535)$ structure nicely reproduced by the model, the $N^*(1650)$ less so. Both $I = 1/2$ resonances generated dynamically.

η-nuclear bound states

two possible mechanisms of generating observable η-nuclear bound states:
- sufficiently large ηN attraction, Re $F_{\eta N} \approx 1$ fm
- moderate attraction combined with fast subthreshold decrease of Im $F_{\eta N}$



left panel - GW model, right panel - CS model
decay widths $\sim$ few MeV (only ηN contributions)
moderately larger widths expected due to $\pi\pi N$ and ηNN contributions

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Summary

- Chirally motivated separable potential models give realistic description of the $\bar{K}N$ and ηN dynamics at energies close to threshold, suitable for in-medium applications.
- The energy shift from threshold to subthreshold $\bar{K}N$ energies provides a link between the shallow $\bar{K}$-nuclear optical potentials obtained microscopically from threshold $\bar{K}N$ interactions and the phenomonelogical deep ones deduced from kaonic atoms data.
- The ηN attraction is reduced in nuclear medium but still strong enough to generate η-nuclear bound states from ^{12}C on. Our model provides very small Im $F_{\eta N}$ that indicates small absorption widths of the η-nuclear states.