The $\bar{K}N$ and related resonances in nuclear matter

Aleš Cieplý

Nuclear Physics Institute, Řež/Prague, Czechia

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Outline:

1. Introduction
2. Separable meson-baryon potentials
3. Dynamically generated resonances/poles
4. $\Sigma^*(1385)$ implementation
5. Nuclear medium impact
6. Summary

Introduction

$\bar{K}N$ interactions

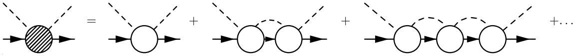
strongly interacting multichannel system with an s-wave resonance near threshold

involved channels	$\pi\Lambda$	$\pi\Sigma$	$\bar{K}N$	$\eta\Lambda$	$\eta\Sigma$	$K\Xi$
thresholds (MeV)	1250	1330	1435	1660	1740	1810

modern theoretical treatment based on an effective chiral Lagrangian
perturbation series do not converge in the vinicity of resonances!
$\Lambda(1405)$ (s-wave) and $\Sigma(1385)$ (p-wave) in between the $\pi\Sigma$ and $\bar{K}N$ thresholds

Solution: construct effective potentials, then use Lippman-Schwinger equation to sum the major part of the perturbation series

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

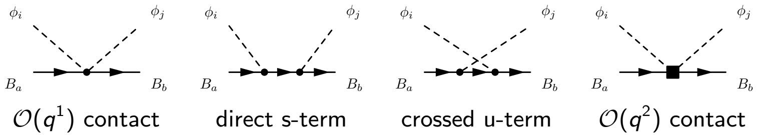


we start with considering only the s-wave interactions and add some p-wave later on

Separable meson-baryon potentials

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

Schematic picture:



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

Some NLO LECs and M_0 fixed by GMO mass splitting formulas and by a relation to the πN sigma term,

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

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

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

- kaonic hydrogen data (SIDDHARTA, 2011)
  energy shift $\Delta E_N(1s) = 283 \pm 36(stat.) \pm 6(syst.)$ eV
  decay width $\Gamma(1s) = 541 \pm 89(stat.) \pm 22(syst.)$ eV
- $K^- p$ threshold branching ratios

$$\gamma = \frac{\sigma(K^- p \to \pi^+ \Sigma^-)}{\sigma(K^- p \to \pi^- \Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \frac{\sigma(K^- p \to \text{charged particles})}{\sigma(K^- p \to \text{all})} = 0.664 \pm 0.011$$

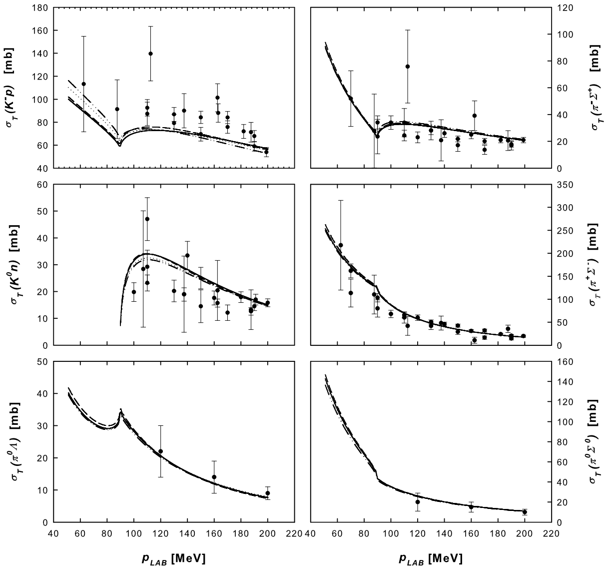
$$R_n = \frac{\sigma(K^- p \to \pi^0 \Lambda)}{\sigma(K^- p \to \text{all neutral states})} = 0.189 \pm 0.015$$

- $K^- p$ low energy cross sections

good data reproduction with the LO TW interaction only (TW1 model)
NLO terms improve the fits (NLO30 model)

A.C., J. Smejkal, NPA 881 (2012) 115

K^-p reaction total cross sections



Dynamically generated resonances/poles

Where do the poles come from?

The amplitude has poles for complex energies z (equal to $\sqrt{s}$ on the real axis) if a determinant of the inverse matrix is equal to zero,

$$\mathrm{det}|f^{-1}(z)| = \mathrm{det}|v^{-1}(z) - G(z)| = 0$$

The origin of the poles can be traced to the

zero coupling limit: $C_{ij} = 0$ for $i \neq j$ (interchannel couplings switched off)

for $C_{i,j\neq i} = 0$ the condition for a pole of the amplitude becomes

$$\prod_n [1/v_{nn}(z) - G_n(z)] = 0$$

There will be a pole in channel n at a Riemann sheet $[+/-]$ (phys./unphys.) if the following condition is satisfied for any complex energy z:

$$\frac{4\pi f_n^2}{C_{nn}(z)} \, \frac{z}{M_n} + \frac{(\alpha_n + \mathrm{i}k_n)^2}{2\alpha_n} \, [g_n(k_n)]^2 = 0$$

Only states with nonzero diagonal couplings $C_{i,j=i}$ can generate the poles!

Dynamically generated resonances/poles

What channels have nonzero diagonal couplings?

For simplicity, we look only at the leading order TW term couplings

sector	channel	ZCL state	resonance
	$\pi\Sigma$	resonance	$\Lambda(1405)$
$S=-1$ $I=0$	$\bar{K}N$	bound	$\Lambda(1405)$
	$K\Xi$	bound	$\Lambda(1670)$
	$\pi\Sigma$	resonance	—
$S=-1$ $I=1$	$\bar{K}N$	virtual	$K^{-}n$ amplitude
			$\pi\Sigma$ photoproduction (CLAS data)
	$K\Xi$	virtual	$\Sigma(1750)$

isovector $\bar{K}N$ related pole:

J. Oller, U.-G. Meißner - Phys. Lett. B 500 (2001) 263

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.-G. Meißner - NPA 725 (2003) 181

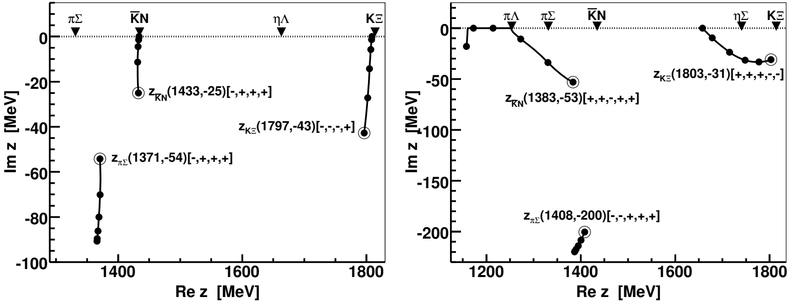
A.C., E. Friedman, A. Gal, D. Gazda, J. Mareš - PRC84 (2011) 045206

A.C., J. Smejkal - Few Body Syst. 54 (2013) 1183

Dynamically generated resonances/poles

Pole movements upon scaling the nondiagonal interchannel couplings

TW1 model, left panel: isoscalar states, right panel: isovector states
The pole positions in the physical limit are emphasized with large empty circles.
The triangles at the top of the real axis indicate the channel thresholds.



$\Lambda(1405)$ resonance

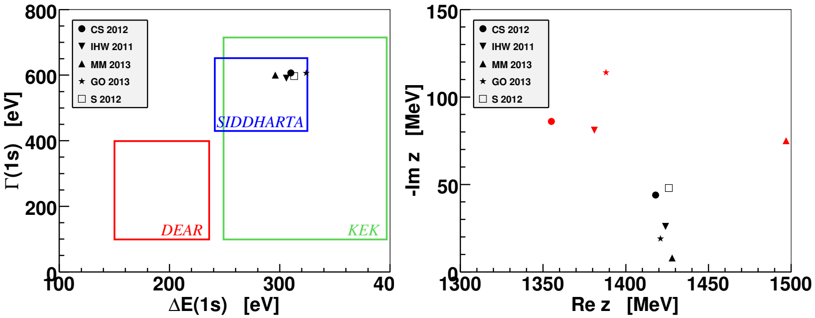
- chiraly motivated models generate dynamically two $I = 0$ poles assigned to the $\Lambda(1405)$ resonance; origin of those poles - $\pi\Sigma$ resonance, $\bar{K}N$ bound state that are moved to their physical resonant positions due to strong $\pi\Sigma$-$\bar{K}N$ coupling
- theoretical models do not agree on exact positions of the poles

$z_{\bar{K}N}$ (MeV)	$z_{\pi\Sigma}$ (MeV)	model
1424-i26	1381-i81	*Ikeda, Hyodo, Weise, NPA 881 (2012) 98*
1418-i44	1355-i86	*A.C., Smejkal, NPA 881 (2012) 115*
1428-i8	1497-i75	*Mai, Meißner, NPA 900 (2013) 51*
1421-i19	1388-i114	*Guo, Oller, PRC 87 (2013) 035202*

- alternate description of experimental data provided with phenomenological potentials that consider only one pole (*Akaishi, Shevchenko*)
- most recent experimental data (CLAS, HADES, AMADEUS) exhibit different line shapes of the $\pi\Sigma$ mass spectra
- possible observance of $\Lambda(1405)$ structure in $K^- d$ reaction at JPARC? (suggested by Jido, Oset, Sekihara; questioned by Miyagawa, Haidenbauer)

model dependence

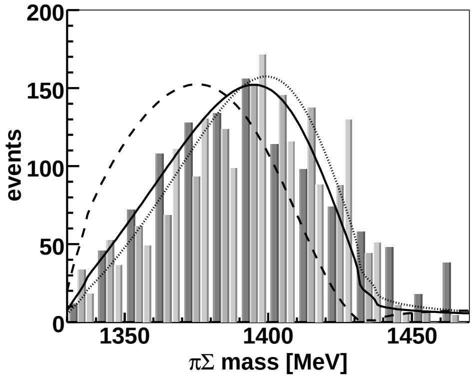
kaonic hydrogen 1s level characteristics and $\Lambda(1405)$ poles



- 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

$\Lambda(1405)$ resonance

$\pi\Sigma$ mass distribution: comparison with results taken from three "compatible" experiments: Thomas (1973), Hemingway (1984), ANKE (2008).
HADES (2013) would fit in nicely too.



$$dN_{\pi\Sigma}/dM \sim \left| T_{\pi\Sigma,\pi\Sigma}(I=0) + r_{KN/\pi\Sigma}\ T_{\pi\Sigma,\bar{K}N}(I=0) \right|^2 p_{\pi\Sigma}$$

$\Lambda(1405)$ resonance

CLAS data on $\pi\Sigma$ distributions vs. theory
$\gamma p \longrightarrow K^+\pi\Sigma$

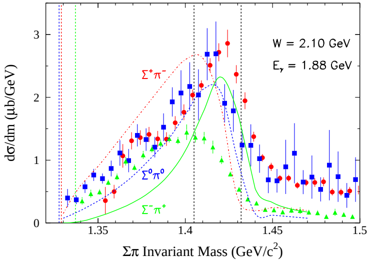
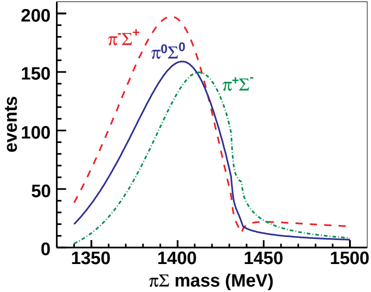


Figure by Schumacher, Moriya (2013),
model predictions by
Nacher, Oset, Toki, Ramos (1999)



$$dN_{\pi\Sigma}/dM \sim \left|F_{\pi\Sigma,K^-p}\right|^2 p_{\pi\Sigma}$$

NLO30 model, A.C., Smejkal (2012)

HADES data from $pp \longrightarrow \pi\Sigma p K^+$ have the peaks at about the same position
we must be missing something !!!

$\Sigma^*(1385)$ implementation

p-wave interactions already considered in:

D. Jido, E. Oset, A. Ramos, Phys. Rev. C 66 (2002) 055203

V. Krejčiřík, Phys. Rev. C 86 (2012) 024003

a new work in progress:

A.C., V. Krejčiřík - paper prepared for publication

general form of the amplitude

$$\mathbf{F}(\mathbf{p} \to \mathbf{p}') = \tilde{F}(\mathbf{p} \to \mathbf{p}') + i\,\sigma \cdot \hat{\mathbf{p}} \times \hat{\mathbf{p}}' \;\tilde{G}(\mathbf{p} \to \mathbf{p}')\,.$$

the amplitudes for partial waves 0^+, 1^+ and 1^- can be treated independently

$$\tilde{F} = F^{0+} + \left(2F^{1+} + F^{1-}\right)(\hat{\mathbf{p}} \cdot \hat{\mathbf{p}}')$$
$$\tilde{G} = F^{1+} - F^{1-}$$

potential decomposition:

$$V = V^{0+} + \left(2V^{1+} + V^{1-}\right)\hat{\mathbf{p}} \cdot \hat{\mathbf{p}}' + \left(V^{1+} - V^{1-}\right) i\sigma \cdot \hat{\mathbf{p}} \times \hat{\mathbf{p}}'$$

$\Sigma^*(1385)$ implementation

leading order interactions in the p-wave sector are represented by direct and crossed diagrams with octet or decuplet baryons in the intermediate state

we consider quite simple model for a start:

- only the TW interaction in the s-wave, the TW1 model
- only the direct diagram with decuplet baryon in the p-wave
- separable form of the p-wave effective potential with the off-shell form factor $g_j^{l=1}(k) = k/[1 + (k/\alpha_j)^2]^{3/2}$

the model is built on an assumption that the $\Sigma^*(1385)$ resonance dominates the p-wave interactions in the discussed energy region, so it might suffice to put the Σ^* baryon in the direct diagram and neglect the other p-wave contributions

$\Sigma^*(1385)$ implementation

our interaction is thus restricted to the TW term

$$v_{ij}^{0+} = -\frac{1}{4\pi f_i f_j}\sqrt{\frac{M_i M_j}{s}}\left[-\frac{1}{4}\,\mathcal{C}_{ij}^{WT}\left(\sqrt{s}-M_i-M_j\right)\right]$$

with $f_i = f_0 = 113$ MeV and the inverse ranges $\alpha_i = \alpha_0 = 701$ MeV fixed by the s-wave TW1 model

and to the 1^+ partial wave potential taken as

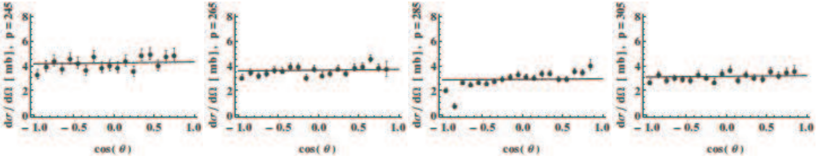
$$v_{ij}^{1+} = -\frac{1}{4\pi f_i f_j}\sqrt{\frac{M_i M_j}{s}}\left(-\frac{1}{\sqrt{2}}\mathcal{C}_{ij}^{d10}\frac{1}{\sqrt{s}-M^*}\right)$$

where the bare M^* mass of the decuplet baryon is fixed to reproduce the $\Sigma^*(1385)$ position, $M^* = 1590$ MeV

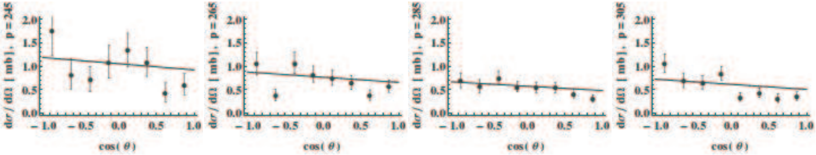
No additional free parameters !!!

p-wave data reproduction

Differential cross section for the $K^- p \to K^- p$ reaction at various energies:



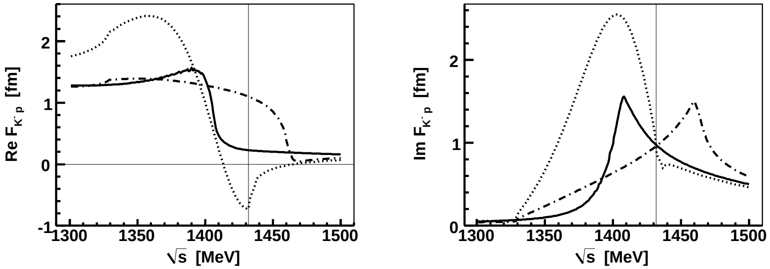
Differential cross section for the $K^- p \to K^0 n$ reaction at various energies:



Computed curves are normalized so that the total cross section is equal to the experimental one. The data are reproduced quite well.

Nuclear medium impact

K^-p amplitude (free and in medium)



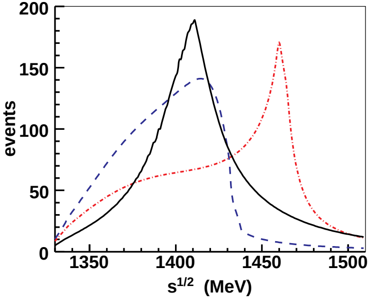
dotted - in vacuum, dot-dashed - Pauli blocked, continuous - Pauli blocked + hadron selfenergies

A.C., J. Smejkal, NPA 881 (2012) 115

- 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.

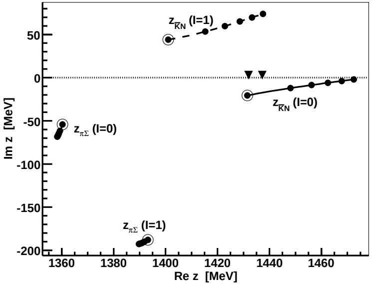
Nuclear medium impact

$\pi^0\Sigma^0$ mass distribution



$$dN_{\pi\Sigma}/dM \sim \left| F_{\pi^0\Sigma^0,K^-p} \right|^2 p_{\pi\Sigma}$$

pole movements due to Pauli blocking upon increasing the nuclear density



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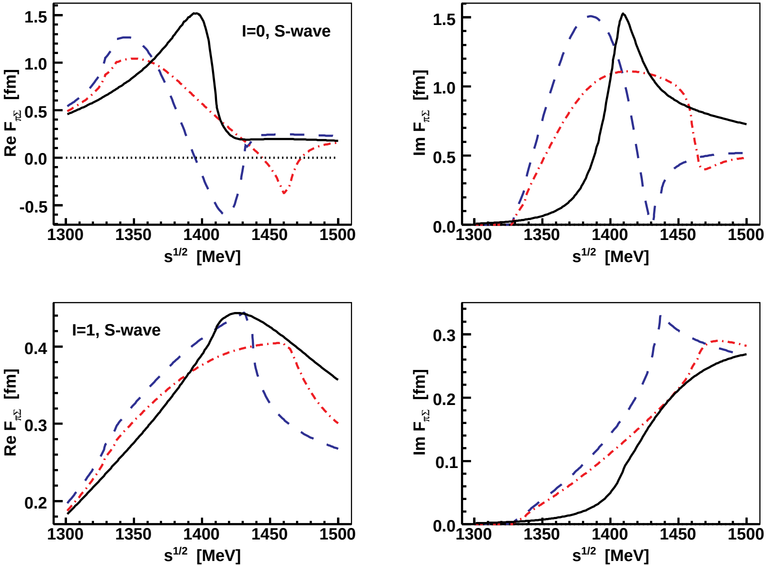
PRC 84 (2011) 045206

in nuclear matter the $\Lambda(1405)$ peak becomes significantly narrower and resembles more a typical Breit-Wigner shape

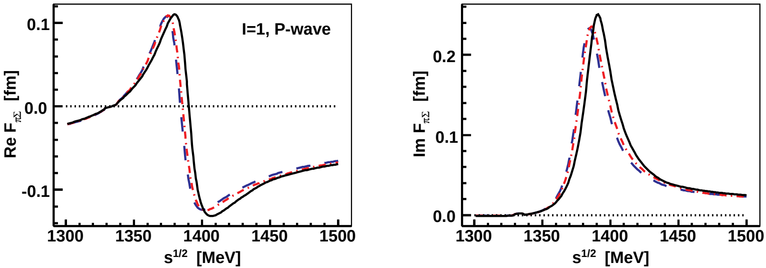
Nuclear medium impact

energy dependence of the $\pi\Sigma$ amplitudes (free and in medium)



Nuclear medium impact

energy dependence of the $\pi\Sigma$ amplitudes (free and in medium)

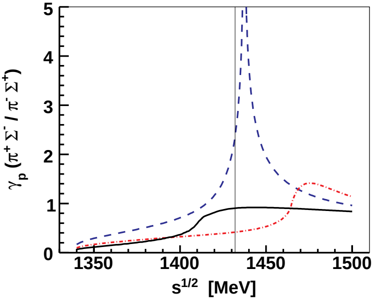


s-wave $\pi\Sigma$ amplitudes:
the higher $\Lambda(1405)$ pole is more relevant in nuclear matter, another clear indication of $I = 1$ structure

p-wave $\pi\Sigma$ amplitudes:
much smaller in magnitude, $\Sigma^*(1385)$ well reproduced, marginal impact of nuclear medium

Nuclear medium impact

nuclear medium impact on the $\pi\Sigma$ branching ratios:



$$\gamma_p = \frac{\sigma(K^- p \to \pi^+\Sigma^-)}{\sigma(K^- p \to \pi^-\Sigma^+)} = \frac{|\ T_0 + \sqrt{\frac{3}{2}}\, T_1\ |^2}{|\ T_0 - \sqrt{\frac{3}{2}}\, T_1\ |^2}$$

where $T_{I=0,1} = \langle \pi\Sigma \mid T \mid \bar{K}N \rangle_{I=0,1}$

$$\gamma_n = \frac{\sigma(K^- n \to \pi^0\Sigma^-)}{\sigma(K^- n \to \pi^-\Sigma^0)} \approx 1$$

strong energy dependence of T_0 close to $\bar{K}N$ threshold leads to the γ_p peak when

$$|\ T_0 - \sqrt{\frac{3}{2}}\, T_1\ | << |\ T_0 + \sqrt{\frac{3}{2}}\, T_1\ |$$

Summary

- Chirally motivated separable potential models give realistic description of the $\bar{K}N$-$\pi\Sigma$ 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.
- Pole movements on the complex energy manifold give us additional insights on the origin of the dynamically generated meson-baryon resonances. The existence of isovector $\bar{K}N$ related pole is supported by recent CLAS data.
- The nuclear medium affects significantly the shape of $\Lambda(1405)$, though the impact on the $\Sigma^*(1385)$ and other p-wave quantities is marginal.

Thanks to my collaborators !!!

E. Friedman, A. Gal, D. Gazda, V. Krejčiřík, J. Mareš, J. Smejkal