K^- Nuclear Quasi-Bound States
in a Chirally Motivated Coupled-Channel Approach

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Summary

In-medium behavior of $\bar{K}$ mesons attracts considerable attention.
Related topical questions include:

- free-space and in-medium $\bar{K}N$ interaction, chiral model tests, nature of $\Lambda(1405)$
- possible existence of (deeply bound, narrow) K^- nuclear clusters
- HI collisions (in-medium modifications, strangeness production)
- structure of compact stars

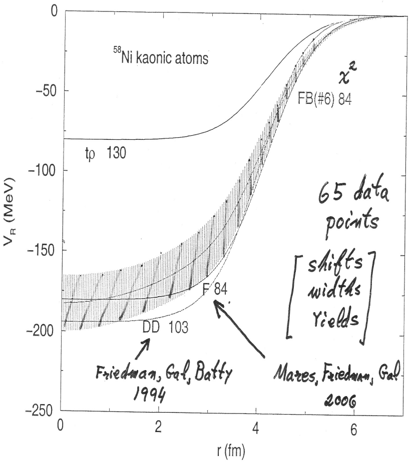
Chiral SU(3) dynamics + coupled channels

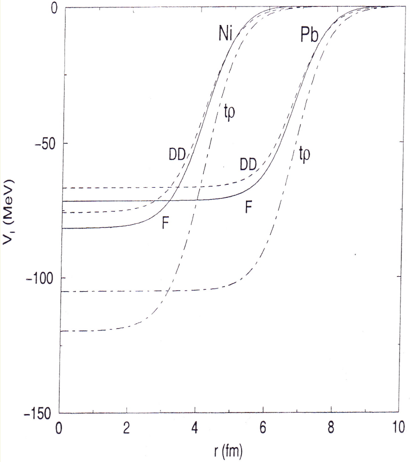
- $\bar{K}N$ interaction:
  - $\Lambda(1405)$ – dynamically generated 2body resonance
    coupled channel chiral approach $\to$ strongly correlated $\bar{K}N - \pi\Sigma$ dynamics provides 2 resonance poles $\to$ $\Lambda(1405)$ is NOT a simple bound state but emerges from the complex interplay of the strongly coupled $\bar{K}N$ and $\pi\Sigma$ channels

- $\bar{K}$ nucleus interaction:
  - leading-order Tomozawa-Weinberg term of the chiral effective Lagrangian: $V_{\bar{K}} = -\frac{3}{8f_\pi^2}\rho \quad \Rightarrow \quad V_{\bar{K}}(\rho_0) \sim -55$ MeV
  - solving $t = v + v\frac{1}{E-H_0}t$
    for coupled channels $(K^-p, \bar{K}^0n, \pi^0\Lambda, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+)$
    $\to \quad V_{\bar{K}}(\rho_0) \sim -(100 \pm 20)$ MeV
  - selfconsistent treatment of kaon propagation in the nuclear medium
    (M. Lutz, PLB 426 (1998) 12)
    $\Rightarrow t^{\mathrm{med}} = v + v\frac{1}{E-H_0-\Pi_i}t$
    $\Pi_{\bar{K}} = 2m_K V_{\mathrm{opt}}^{\bar{K}} \sim t(\rho)\rho$, $\Pi_N = 2m_N V_{\mathrm{opt}}^{N} \sim V_0\rho/\rho_0$
    LS equation $\quad\to\quad t_{\bar{K}N} \quad\to\quad V_{\mathrm{opt}}^{\bar{K}} \sim \Pi_{\bar{K}} \quad\to\quad$ LS equation
    $\to \quad V_{\bar{K}}(\rho_0) \sim -(40 - 60)$ MeV

K^- atoms

- Phenomenology (e.g., DD, RMF):





RMF vs. Chiral Approach

$$(-\nabla^2 - E_{K^-}^2 + m_K^2 + \Pi_{K^-})K^- = 0$$

- $\mathrm{Re}\,\Pi_{K^-}$ from RMF — *energy independent*
- $\mathrm{Im}\,\Pi_{K^-} \approx f\,W_0\,\rho_N(r)$ — *f is energy dependent*
  W_0 constrained by kaonic atom data, constant!
  Absorption through:
  - pionic conversion modes: $\bar{K}N \to \pi\Sigma, \pi\Lambda$
  - nonmesonic modes: $\bar{K}NN \to YN$

- $\Pi_{K^-} \approx t\,\rho_N(r)$
  t from CHIRAL MODEL $\Rightarrow t(E,\rho)$!
  — *energy and density dependent*
  Absorption through:
  - $\bar{K}N \to \pi\Sigma, \pi\Lambda$
  - $\bar{K}NN \to YN$ NOT INCLUDED

Chiral model

$$\left[\nabla^2 + \omega_K^2 - m_K^2 + 4\pi \frac{\sqrt{s}}{m_N} F_{K^-N}(\vec{p}, \sqrt{s}; \rho)\rho\right] \phi_K = 0 \ ,$$

$$\omega_K = m_K - \mathcal{B}_K - V_c \ \text{ and } \ \mathcal{B}_K = B_K + i\Gamma_K/2$$

- two-body arguments of the in-medium scattering amplitude $\vec{p}$ (relative $K^- N$ momentum) and $\sqrt{s}$ ($s = (E_K + E_N)^2 - (\vec{p}_K + \vec{p}_N)^2$):

$$\sqrt{s} \sim E_{th} - B_N - B_K - \xi_N \frac{p_N^2}{2m_N} - \xi_K \frac{p_K^2}{2m_K} \ ,$$

$$p^2 \approx \xi_N \xi_K (2m_K \frac{p_N^2}{2m_N} + 2m_N \frac{p_K^2}{2m_K}) \ , \quad \text{where} \quad \xi_{N(K)} = m_{N(K)}/(m_N + m_K)$$

$$\Rightarrow$$

$$\sqrt{s} \sim E_{th} - B_N - \xi_N B_K - 15.1(\frac{\rho}{\rho_0})^{2/3} + \xi_K \mathrm{Re} V_{K^-}(\rho) \ ,$$

$$p^2 \approx \xi_N \xi_K [2m_K T_N (\frac{\rho}{\rho_0})^{2/3} - 2m_N(B_K + \mathrm{Re} V_{K^-}(\rho))]$$

- $V_K, B_K \ \Rightarrow$ selfconsistent solution
- Weise, Härtle (NPA 804 (2008) 173) [WH]: $\sqrt{s} = E_{th} - B_K - V_c$

Chiral model

- chirally motivated coupled channel separable potential model (A. Cieply, J. Smejkal, Eur. Phys. J A 43, 191 (2010))

  - coupled channels: $\pi\Lambda$, $\pi\Sigma$, $\bar{K}N$, $\eta\Lambda$, $\eta\Sigma$, $K\Xi$
  - $V_{ij}(p,p';\sqrt{s}) = \sqrt{\frac{1}{2\omega_i}\frac{M_i}{E_i}} g_i(p) \frac{C_{ij}(\sqrt{s})}{f_\pi^2} g_j(p') \sqrt{\frac{1}{2\omega_j}\frac{M_j}{E_j}}$, $g_j(p) = \frac{\alpha_j^2}{p^2+\alpha_j^2}$
  - $F_{ij}(p,p',\sqrt{s}) = g(p) f_{ij}(\sqrt{s}) g(p')$

    where

$$f_{ij}(\sqrt{s}) = -\frac{1}{4\pi f_\pi^2}\sqrt{\frac{M_i M_j}{s}}[(1 - C(\sqrt{s})G(\sqrt{s}))^{-1}C(\sqrt{s})]_{ij}$$

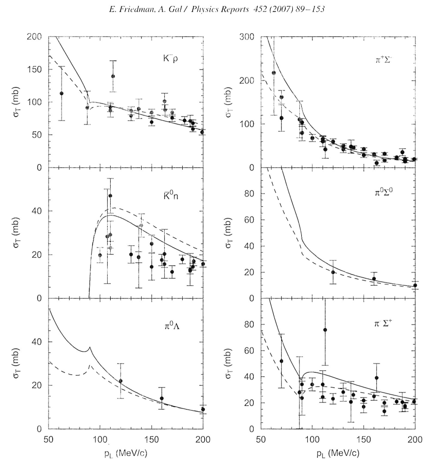
$$G_i(\sqrt{s};\rho) = \frac{1}{f_\pi^2}\frac{M_i}{\sqrt{s}}\int_{\Omega_i(\rho)}\frac{d^3\vec{p}}{(2\pi)^3}\frac{g_i^2(p)}{p_i^2 - p^2 - \Pi_i + i0}$$

- selfenergies $\Pi_i \Longrightarrow$ selfconsistent solution

$$\Pi_K(\omega_K,\rho) = 2\omega_K V_{K^-} \sim -4\pi\frac{\sqrt{s}}{m_N}F_{K^-N}\rho \ , \quad \Pi_i = V_0\rho/\rho_0$$

Chiral model

- free parameters of the model fitted to the experimental data:
  - $K^- p$ low energy Xsections for elastic scattering and reactions to $\bar{K}^0 N$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Lambda$, and $\pi^0\Sigma^0$



Chiral model

- K^-p threshold branching ratios γ, R_c, R_n

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

$$R_c = \frac{\Gamma(K^-p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \to \text{all inelastic channels})} = 0.664 \pm 0.011$$

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

Chiral model

- kaonic hydrogen strong interaction shift ΔE_{1s} and its decay width Γ_{1s} (KEK, DEAR, SIDDHARTA)

$$\longrightarrow$$

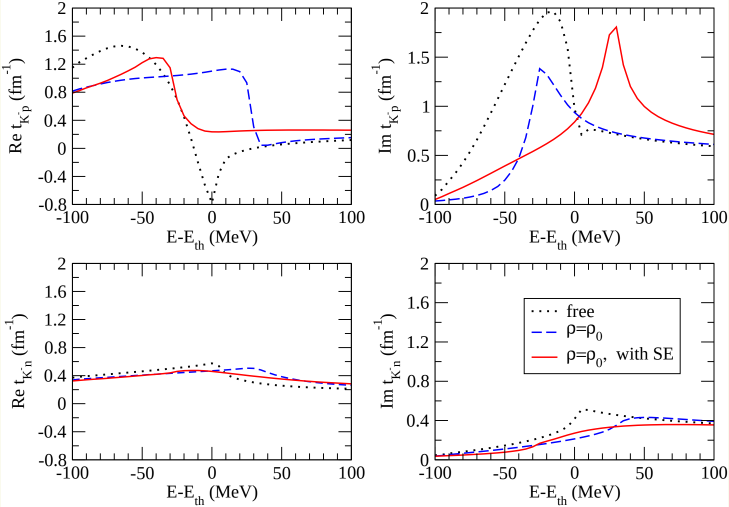
1) CS30: $\mathscr{L}(2)$ + selfenergies (SE)
(A. Cieply, J. Smejkal, Eur. Phys. J A 43 (2010) 191;

A. Cieply, E. Friedman, A. Gal, D. Gazda, J. Mares, PLB 702 (2011) 402)

2) SIDDHARTA $\rightarrow$ TW1

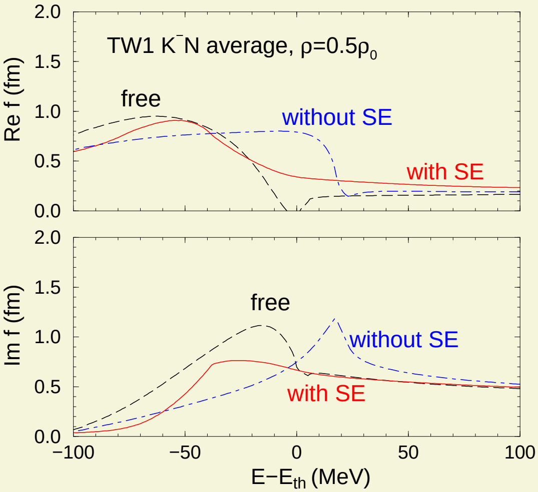
(A. Cieply, E. Friedman, A. Gal, D. Gazda, J. Mares, arXiv:1108.1745[nucl-th])

Scattering Amplitudes



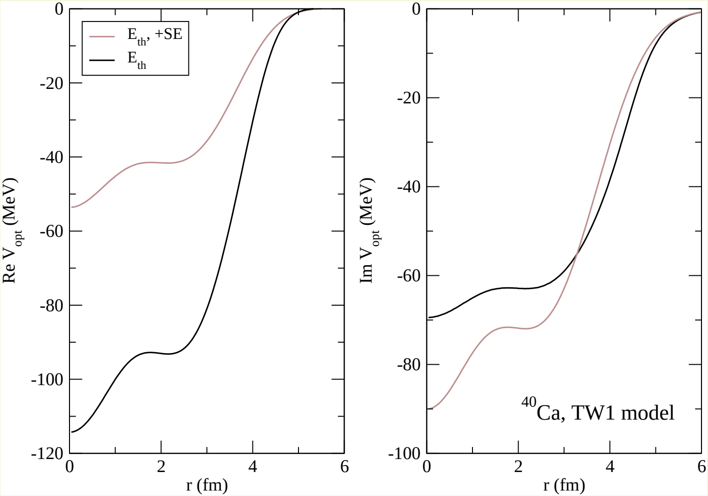
- $f_{K^-p} = 1/2(f^{I=0}_{KN} + f^{I=1}_{KN})$ affected by the $I = 0$ $\Lambda(1405)$
- $f_{K^-n} = f^{I=1}_{KN}$ not affected

Scattering Amplitudes

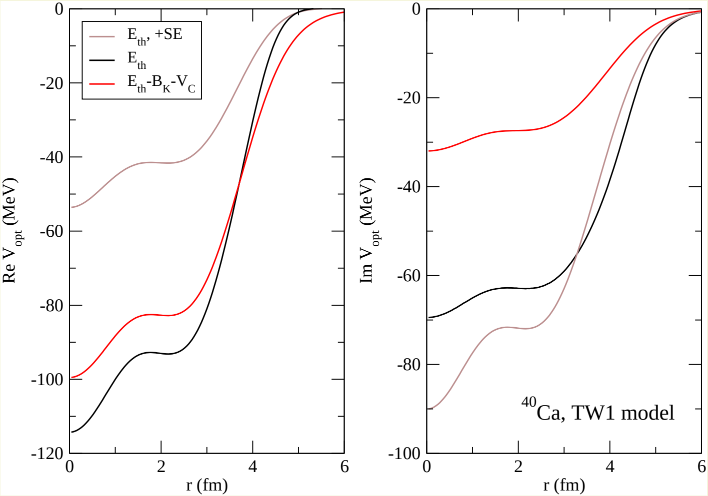


- Energy dependence of the amplitude $f_{K^-N} = 1/2(f_{K^-p} + f_{K^-n})$ in TW1 model
- at threshold the real part of the "with SE" amplitude is $\approx 1/2$ of that "without SE" $\longrightarrow$ corresponds to $\mathrm{Re}V_K \sim 40$ MeV

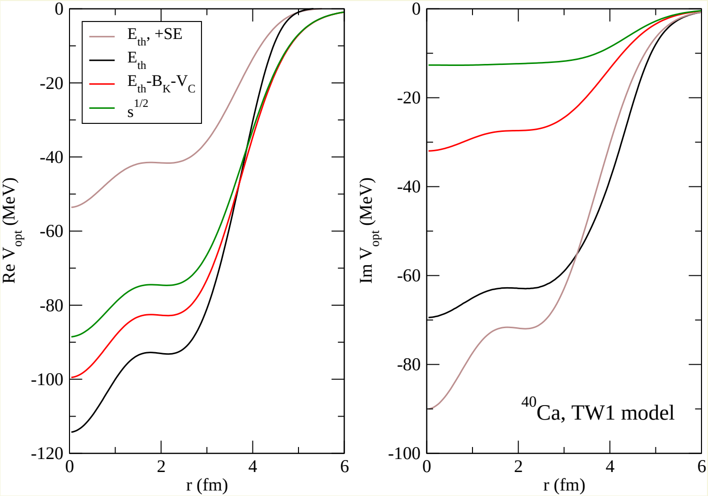
K^- potentials



K^- potentials



K^- potentials



K^- potentials

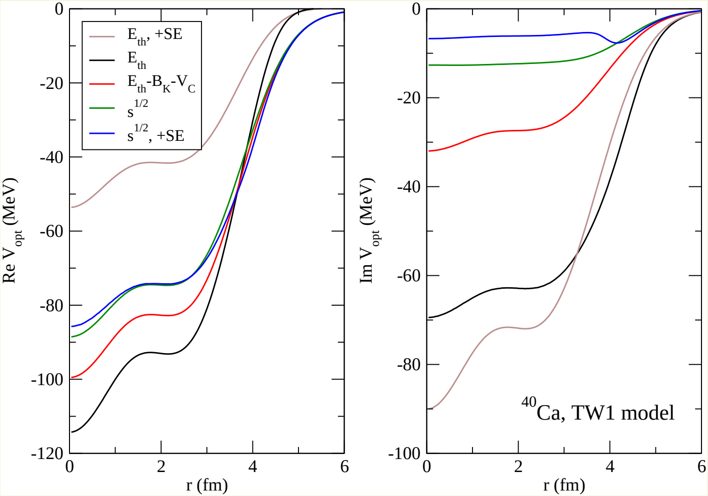


Table: TW1 model, the effect of the energy dependence

		C	O	Ca	Zr	Pb
E_{th}, NOSE	B_K	61.1	57.5	83.4	96.0	104.8
	Γ_K	149.1	135.9	150.7	151.2	143.9
$\sqrt{s}$, NOSE	B_K	44.6	45.3	63.0	72.9	79.0
	Γ_K	59.3	54.9	43.1	34.0	26.4
E_{th}, + SE	B_K	(-0.9)	6.4	25.0	39.0	53.4
	Γ_K	(137.6)	120.2	141.8	141.0	129.1
$\sqrt{s}$, + SE	B_K	42.4	44.9	58.8	68.9	76.3
	Γ_K	16.5	16.2	12.0	11.5	11.3
$V_{K^-}^{\mathrm{RMF}}$	B_K	49.1	47.7	60.5	69.6	76.8

Kaonic nuclei

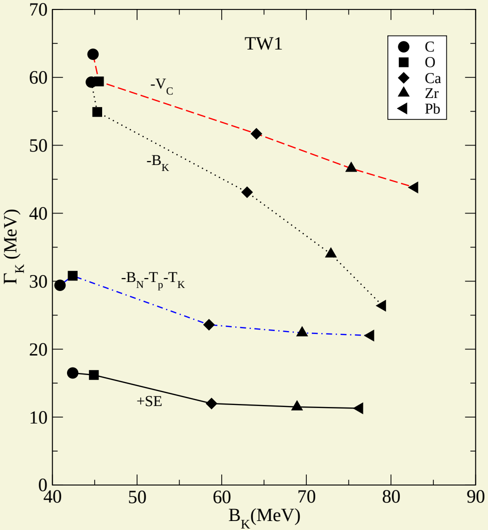


Fig. B_{K^-} and Γ_{K^-} of $1s$ K^- nuclear states, calculated by applying selfconsistently several prescriptions of subthreshold $\sqrt{s}$ extrapolation to in-medium TW1 amplitudes.

P-wave interactions

- *P*- wave interactions - might be important in tightly bound K^- nuclei, when K^- can have large momentum
  (S. Wycech, A.M. Green, [nucl-th/0501019])
- parametrization of Weise+Härtle (NPA 804 (2008), 173)
  dominated by $I = 1$ $\Sigma(1385)$ + small background term d:

$$F^{pwave}_{K^-p} = 1/2 F^{pwave}_{K^-n} = \frac{M_N}{\sqrt{s}} C(s)\vec{q}\vec{q}' \ ,$$

$$C(s) = \frac{\sqrt{s}\gamma}{M^2 - s - i\sqrt{s}\Gamma(s)} + d \ ,$$

where $\gamma = 0.42/m_K^2$, $d = 0.06$ fm^3, $M = 1385$ MeV, $\Gamma(s) = 40$ MeV at resonance

P-wave interactions

Table: TW1 model, the effect of p wave

		C	O	Ca	Zr	Pb
[WH]	B_K	44.8	45.5	64.1	75.3	82.8
	Γ_K	63.4	59.4	51.7	46.6	43.8
[WH], p wave	B_K	39.7	43.7	69.1	79.9	87.2
	Γ_K	85.6	73.6	55.5	46.7	44.3
$\sqrt{s}$	B_K	40.9	42.4	58.5	69.5	77.6
	Γ_K	29.4	30.8	23.6	22.4	22.0
$\sqrt{s}$, p wave	B_K	46.0	46.0	60.8	71.5	79.4
	Γ_K	27.5	29.6	22.4	21.3	21.0

TW1 vs. CS30 model

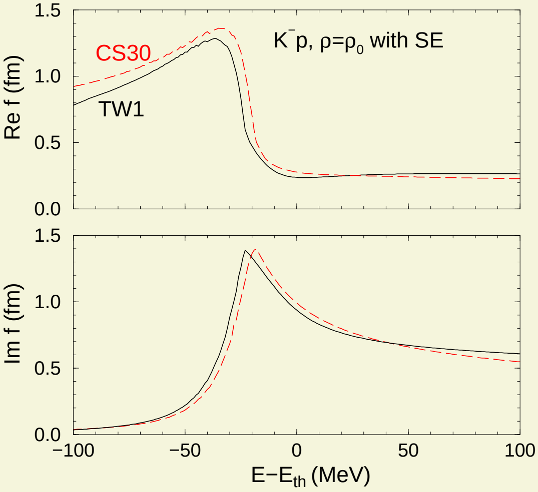


Fig. Energy dependence of in-medium $K^- p$ amplitudes at ρ_0 in models TW1 (solid lines) and CS30 (dashed lines)

TW1 vs. CS30 model

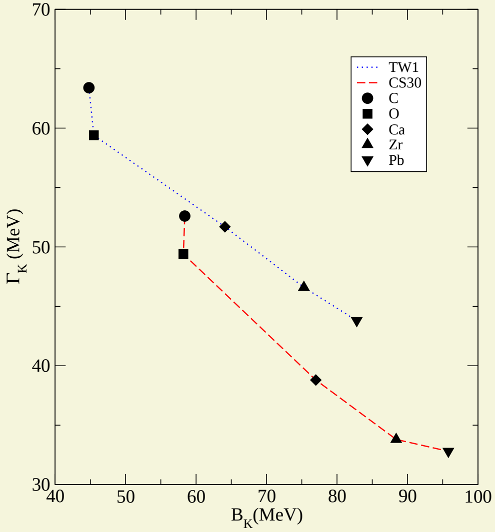


Fig. B_{K^-} and Γ_{K^-} of $1s$ K^- nuclear states, calculated by applying selfconsistently the subthreshold [WH] ($\sqrt{s} = E_{th} - B_K - V_c$) extrapolation to the TW1 and CS30 in-medium amplitudes.

2N absorption in kaonic nuclei

- 2N absorption – from phenomenology:

$$+\mathrm{Im}\,\Pi_{K^-} = 0.2 f_{2\Sigma}\, W_0\, \rho_N^2(r)/\tilde{\rho}_0$$

f_{iY} kinematical suppression factors
(reduced phase space)

W_0 constrained by kaonic atom data

Absorption through:

- nonmesonic modes $\propto \rho_N^2(r)$
  $\bar{K}NN \to YN$+240 MeV (20%)

CS30 model + 2N absorption

Table: B_K and Γ_K in selected nuclei, CS30 model and various options

		C	O	Ca	Zr	Pb
[WH]	B_K	58.4	58.2	77.0	86.7	95.8
	Γ_K	52.6	49.8	33.8	33.8	32.8
$\sqrt{s}$	B_K	52.0	53.0	69.7	81.5	89.6
	Γ_K	19.6	21.6	14.4	13.6	14.0
+SE	B_K	50.7	52.5	68.2	79.3	86.6
	Γ_K	13.0	12.8	10.9	11.0	10.9
+dyn.	B_K	55.7	56.0	70.2	80.5	87.0
	Γ_K	12.3	12.1	10.8	10.9	10.8
+ 2N abs.	B_K	54.0	55.1	67.6	79.6	86.3
	Γ_K	44.9	53.3	65.3	48.7	47.3

Summary

- We have shown within in-medium chirally motivated coupled channel CS30 and TW1 models how to incorporate strong E and ρ dependence of the K^-N scattering amplitude $F_{K^-N}(\sqrt{s},\rho)$ into a selfconsistent evaluation of the Π_K (V_K).
- Chiral models give relatively deeply bound K^- nuclear states with $B_{K^-} \sim 50 - 100$ MeV in heavier nuclei (A + model dependence). The $\bar{K}NN \rightarrow YN$ channel contributes significantly to the widths ($\Rightarrow \Gamma_{K^-} > 40$ MeV)
- The effects of p-wave interactions are found to be secondary to those of s waves.