Interaction of the Θ^+ with the nuclear medium and its effect on the kaon optical potential

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Introduction: The Θ^+ particle

- Discovery of Θ^+ by LEPS at Spring8:

  "EVIDENCE FOR A NARROW S = +1 BARYON RESONANCE IN PHOTOPRODUCTION FROM THE NEUTRON." By LEPS Collaboration (T. Nakano et al.). Phys.Rev.Lett.91:012002,2003

  "The LEPS group have reported the first evidence for a pentaquark state with quark configuration "$uudd\bar{s}$", which is remarkably consistent with the prediction by Russian theorists... The pentaquark is a new form of hadron and the discovery may have significant impact on the possibility of the existence of the other kinds of quark matter and the understanding of the origin of matter in the early universe." See also: http://www.rcnp.osaka-u.ac.jp/RCNPhome/5quark-e.html

- Confirmed by several groups, but also negative results (three $\rightarrow$ two stars in the PDG). $I(J^P) = 0(?^?)$

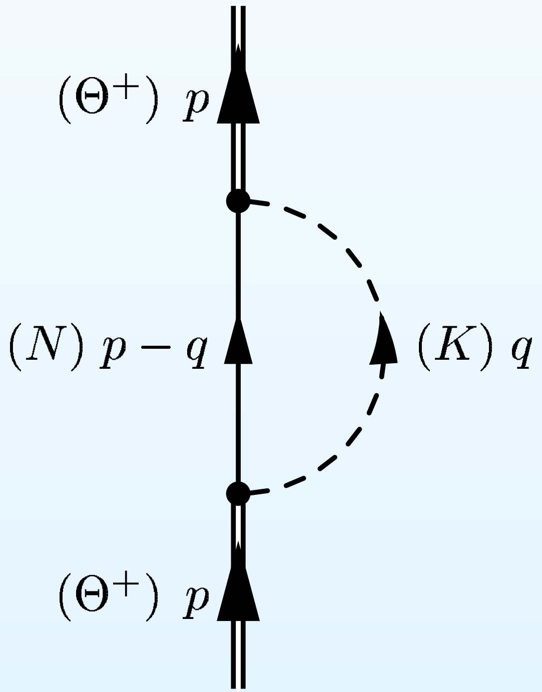
- Mass $=1534.3 \pm 2.5$, Width $=0.9 \pm 0.3$ PDG

  Further references exp + theo : http://www.rcnp.osaka-u.ac.jp/$\sim$hyodo/research/Thetapub.html by T. Hyodo

  Recent review with experimental compilation: K.H. Hicks, Prog. Part. Nucl. Phys. 55, 647 (2005) [arXiv:hep-ex/0504027]

Introduction: The Θ^+ particle

- Mass $=1534.3 \pm 2.5$, Width $=0.9 \pm 0.3$ PDG *It is very narrow! (Typical widths ~ 100 MeV)*
- NK is the only strong decay mode allowed for a $S=1$ particle of this mass.



Introduction: Θ^+ nuclear effects?

In many experiments Θ^+ is produced in nuclei

- How does the Θ^+ interacts with the nuclei?
- Mass and/or width changes?
- Other decay channels

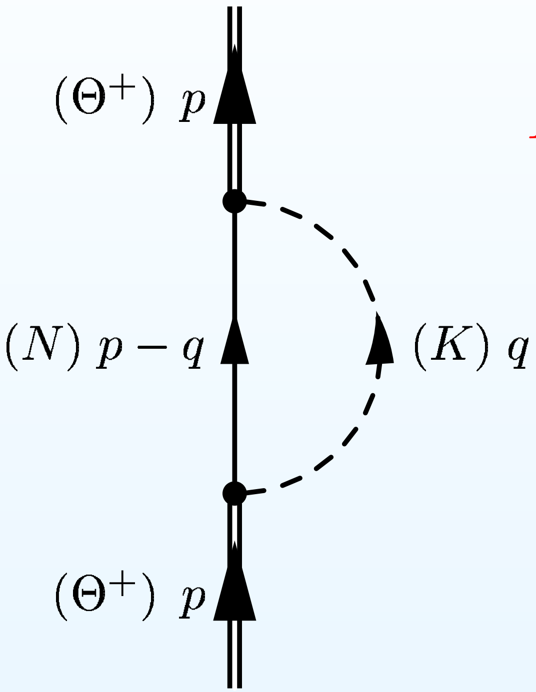
And if the interaction is attractive and strong enough...

Are there **S=1** Hypernuclei?

How does Θ^+ influence the rather soft, "featureless" KN (and kaon nucleus) interaction?

Contents

Θ^+ selfenergy from KN decay



KN couplings

- $t_{K^+n} = g_{K^+n}; \quad t_{K^0p} = -g_{K^+n}$
  for $J^P = \frac{1}{2}^-$
- $t_{K^+n} = -i\bar{g}_{K^+n}\vec{\sigma}\vec{q}$; $t_{K^0p} = i\bar{g}_{K^+n}\vec{\sigma}\vec{q}$
  for $J^P = \frac{1}{2}^+$

For the $L=0$ case

$$\Sigma_{KN}(p) = 2i\int \frac{d^4q}{(2\pi)^4}(-ig_{K^+n})^2 \frac{M}{E_N} \frac{i}{p^0-q^0-E_N+i\epsilon} \frac{i}{q^2-m_K^2+i\epsilon}$$

Θ^+ selfenergy from KN

$$\Sigma_{KN}(p) = 2i \int \frac{d^4q}{(2\pi)^4} (-i g_{K^+n})^2 \frac{M}{E_N} \frac{i}{p^0 - q^0 - E_N + i\epsilon} \frac{i}{q^2 - m_K^2 + i\epsilon}$$

$\longrightarrow$ The imaginary part of Σ_{KN} gives the width

$$\Gamma = -2\,\mathrm{Im}\,\Sigma_{KN} = \frac{g_{K^+n}^2}{\pi} \frac{M}{M_{\Theta^+}} q_{on}$$

$\longrightarrow$ The experimental width allows to obtain g_{K^+n}

· The formulas for $L = 1$ are obtained by the substitution

$$g_{K^+n}^2 \rightarrow \bar{g}_{K^+n}^2 \vec{q}^{\,2}$$

Σ_{KN} scales like Γ !

Medium effects

- The nucleon propagator is modified

$$\frac{1}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) + i\epsilon} \longrightarrow$$
$$\frac{1 - n(\vec{p}-\vec{q})}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) - V_N + i\epsilon} + \frac{n(\vec{p}-\vec{q})}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) - V_N - i\epsilon} \,,$$

  with $n(.)$ the nucleon occupation number

  and $V_N = -k_F^2/2M_N$ the Thomas-Fermi potential

- The kaon propagator is modified

$$\frac{1}{q^2 - m_K^2 + i\epsilon} \longrightarrow \frac{1}{q^2 - m_K^2 - \Pi_K(q,\rho)} \,,$$

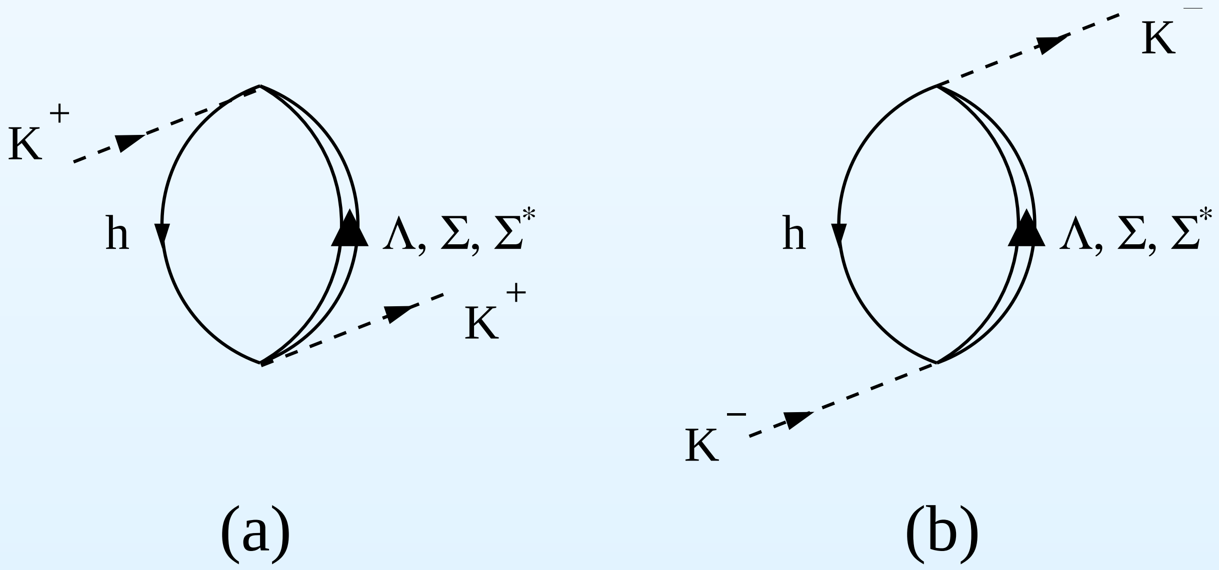
  where $\Pi_K(q,\rho)$ is the kaon selfenergy

Medium effects - The kaon

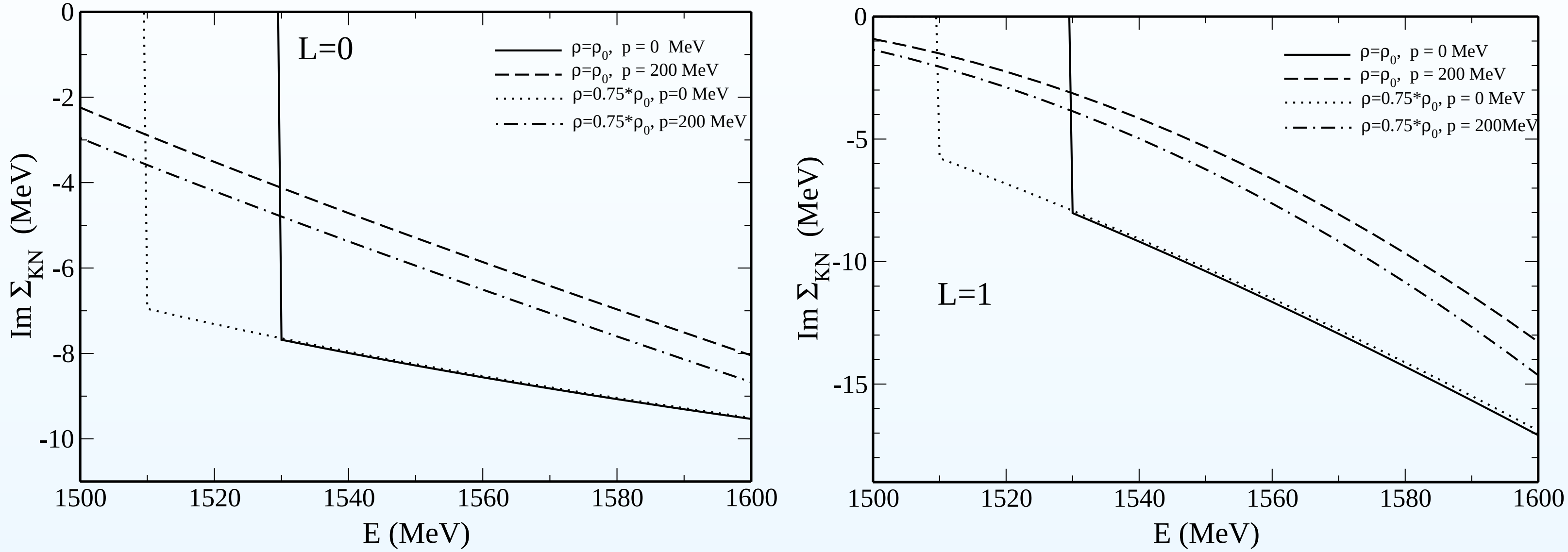
- $\Pi_K(q,\rho)$ contains a $s-$wave and a $p-$wave part. The $s-$wave part is well approximated by

$$\Pi_K^{(s)}(\rho) = 0.13\, m_K^2 \rho/\rho_0 \;\; [\text{MeV}^2]\,,$$

- The quite small $p-$wave part includes only crossed terms (a) of $Y h$ excitations



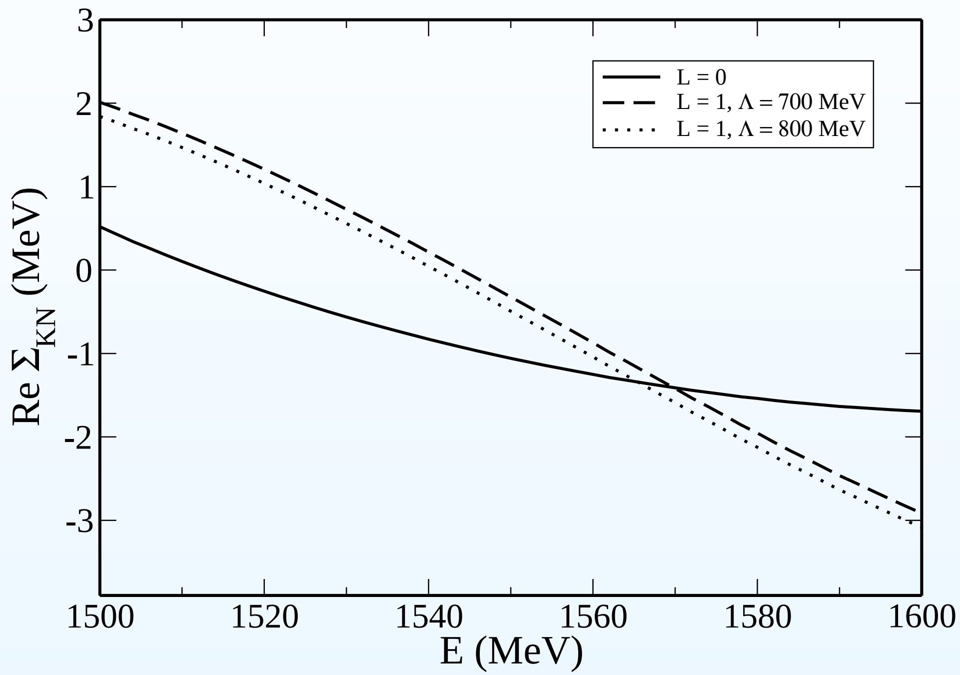
In medium $\Theta^+ \to KN$ width



ImΣ_{KN} for $L = 0$ and 1, obtained assuming a free width of 15 MeV

- The finite Θ^+ momentum makes Pauli blocking effective at the Θ^+ mass and the width is further reduced !
- Small width for possible bound states.

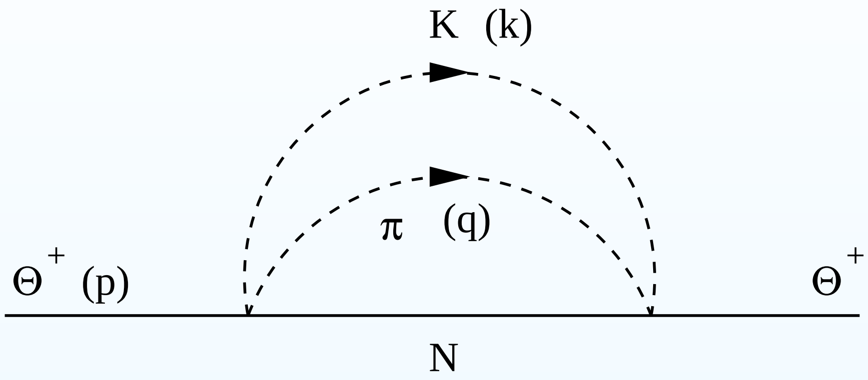
Real part of the selfenergy $\Theta^+ \to KN$



ReΣ_{KN} at $\rho = \rho_0$. A momentum of the Θ^+ of 200 MeV is taken

- Loop integral is convergent after subtraction of the vacuum selfenergy for the $L = 0$ case and weakly cut off dependent for the $L = 1$ case.
- Very small potential!
- Qualitatively agrees with previous work. *H.C. Kim et al J. Korean Phys. Soc. 46, 393 (2005)*

Θ^+ selfenergy from the two-meson cloud

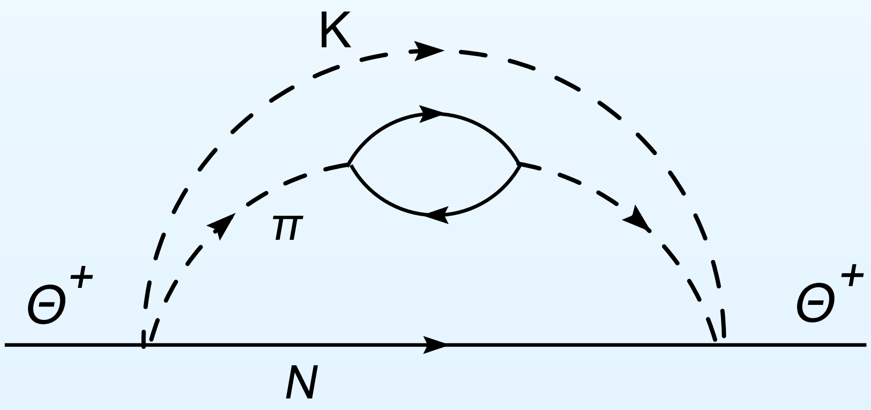


Two-meson Θ^+ selfenergy diagram.

- Θ^+ is below the $N\,K\,\pi$ threshold and thus, this term doesn't contribute to the width in vacuum $\rightarrow$ $(\mathrm{Im}\,\Sigma = 0)$.
- No direct information on the couplings.
- Is it relevant?

" $\Theta^+ \to K\, N\, \pi$" selfenergy

- In contrast with the kaons the pions are strongly affected by the nuclear medium!
  - Absorption, excitation of *particle-hole* and $\Delta-$*hole* states
  - Strong attractive potential
- In the nuclear medium, new channels are open like $\Theta^+ \to K\, N\, (p-h)$, as a *particle-hole* excitation requires only a few MeV's



$\Theta^+ \to K\, N\, \pi$ selfenergy

Some assumptions: *A. Hosaka et al., Phys. Rev. C71, 045205 (2005)*

- Θ^+ is $J^P = \frac{1}{2}^+$ and belongs to an $SU(3)$ antidecuplet
- Two $SU(3)$ symmetric Lagrangians are selected
  - $\mathcal{L}_1 = i g_{\bar{10}} \epsilon^{ilm} \bar{T}_{ijk} \gamma^\mu B^j_l (V_\mu)^k_m$ (vector coupling)
  - $\mathcal{L}_2 = \frac{1}{2f} \tilde{g}_{\bar{10}} \epsilon^{ilm} \bar{T}_{ijk} (\phi \cdot \phi)^j_l B^k_m$ (scalar coupling)

    V_μ two-meson vector current, $V_\mu = \frac{1}{4f^2}(\phi \partial_\mu \phi - \partial_\mu \phi \phi)$,

    T_{ijl}, B^j_l, ϕ^k_m $SU(3)$ tensors for baryon antidecup., baryon octet, meson octet
  - Minimal number of derivatives

    Phenomenological constraints from the antidecuplet baryon decays into MMB and the contribution to the mass splitting from the MM cloud

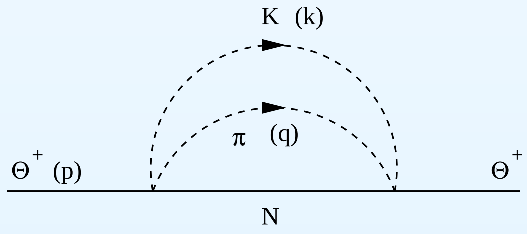
    $\Theta^+(1540)$, $N^*(1710)$, $\Sigma(1770)$, $\Xi(1860)$

$\Theta^+ \to K\,N\,\pi$ selfenergy

- $N^*(1710)$ couples strongly to the same $SU(3)$ antidecuplet.
- The couplings are fitted to the
  $N^*(1710) \to N(\pi\pi, p\text{-wave}, I=1)$ and to the
  $N^*(1710) \to N(\pi\pi, s\text{-wave}, I=0)$ decay widths

$\longrightarrow$ Θ^+ selfenergy is a combination of pieces like

$$\Sigma^j(p) = -\int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} |t^j|^2 \times$$
$$\times \frac{1}{k^2 - m_1^2 + i\epsilon} \; \frac{1}{q^2 - m_2^2 + i\epsilon} \; \frac{M}{E_N} \; \frac{1}{p^0 - k^0 - q^0 - E_N + i\epsilon}$$
$$(j = S, V)$$



$\longrightarrow$ Real part is regularized with a cutoff [a]

[a] In vacuum this selfenergy provides a mass reduction of ≈ 100 MeV for the Θ^+

Medium effects

- The pion propagator is modified

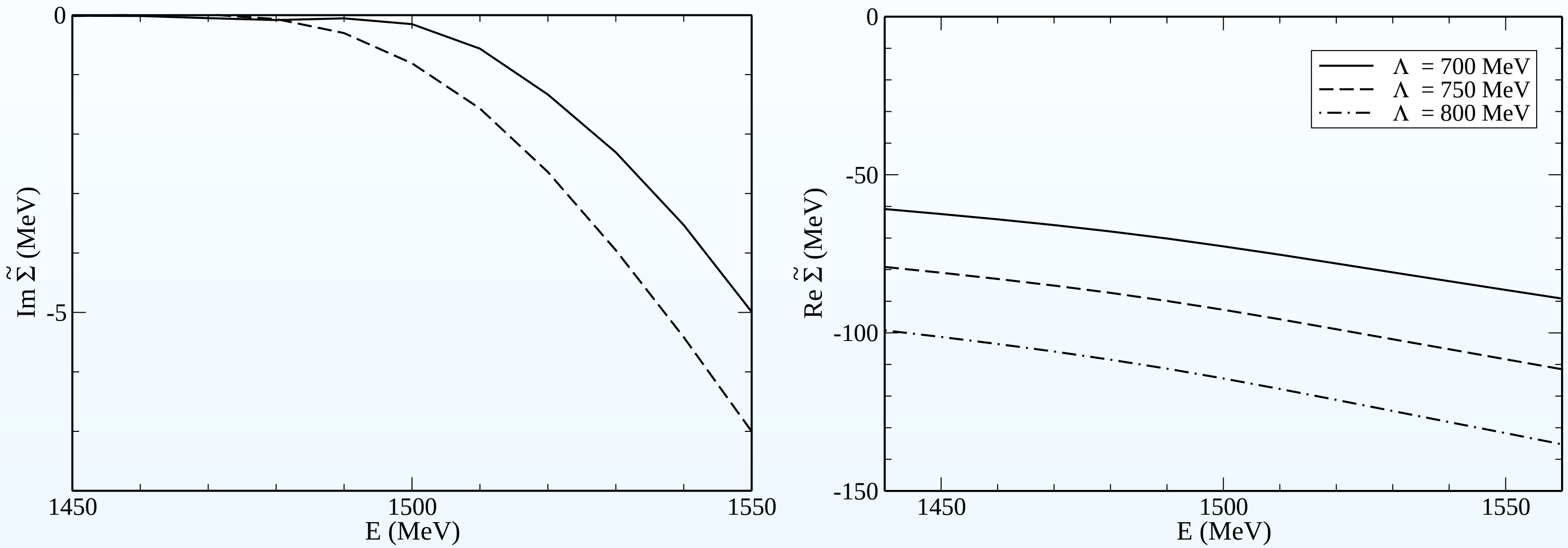
$$\frac{1}{q^2 - m_\pi^2 + i\epsilon} \rightarrow \frac{1}{q^2 - m_\pi^2 - \Pi_\pi(q,\rho)} \, ,$$

where $\Pi_\pi(q,\rho)$ is the well known [a] pion selfenergy. The main ingredients are:

  - Coupling to *nucleon-hole* and Δ*-hole* excitations
  - Short range correlations.

[a] i.e. T.E.O. Ericson and W. Weise's Pions in Nuclei or E. Oset, H. Toki and W. Weise, Phys. Rept. 83 (1982) 281

Σ from the $\Theta^+ \to K\, N\, \pi$ channel



- At 1540 MeV would add around 8 MeV to the width (for $\rho = \rho_0$)
- Large attraction, strong enough to bind the Θ^+ in any nucleus.
- For typical ($\Delta E \sim -20$ MeV) bound states the width would be below 8 MeV.

Bound Θ^+ states?

$V = -60$ MeV ρ/ρ_0		$V = -120$ MeV ρ/ρ_0	
E_i (MeV), ^{12}C	E_i (MeV), ^{40}Ca	E_i (MeV), ^{12}C	E_i (MeV), ^{40}Ca
-34.0 (1s)	-42.6 (1s)	-87.3 (1s)	-98.2 (1s)
-14.6 (1p)	-30.9 (1p)	-59.5 (1p)	-83.3 (1p)
-0.3 (2s)	-18.7 (1d)	-32.0 (2s)	-67.5 (1d)
	-17.9 (2s)	-31.9 (1d)	-65.9 (2s)
	-6.3 (1f)	-8.6 (2p)	-50.8 (1f)
	-5.6 (2p)	-5.6 (1f)	-48.5 (2p)
			-33.5 (1g)
			...

- Θ^+ binding energies

The kaon potential: A long-standing problem

KN interaction believed to be rather soft (no $S = +1$ baryonic resonances)

- In contrast, $\bar{K}N$ dominated by $\Lambda(1405)$

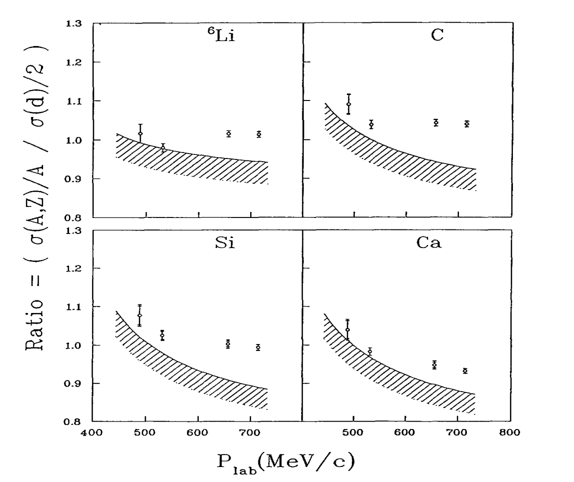
Single particle kaon potential (selfenergy) usually approximated by $T\rho$ (low density theorem)

- ≈ 30 MeV repulsion ($S-$wave selfenergy $\rightarrow \approx 6\%$ mass increase
- smooth energy dependence

Ex: $\Pi_K(\rho) = 0.13\, m_K^2\, \frac{\rho}{\rho_0}$ *from L.O. meson baryon* χ*PT N. Kaiser et al., Nucl. Phys. A594 (1995) 325; A612 (1997) 297*

A long-standing problem

However: <u>*All*</u> theoretical models based on a $T\rho$ *fail* to reproduce $\sigma(K^+ \text{ nucleus})$: $10-20\%$ below data



Bugg et al ('68)
Mardor et al ('90)
Krauss et al ('92)
Chen et al ('92)
$(*)$ *Sawafta et al ('93)*
Weiss et al ('94)
Chen et al ('95)
Friedman et al ('97)

Several ("conventional") mechanisms explored:

- nucleon swelling
- meson exchange currents
- medium effects in exchanged vector mesons

$\longrightarrow$ *unsatisfactory results*

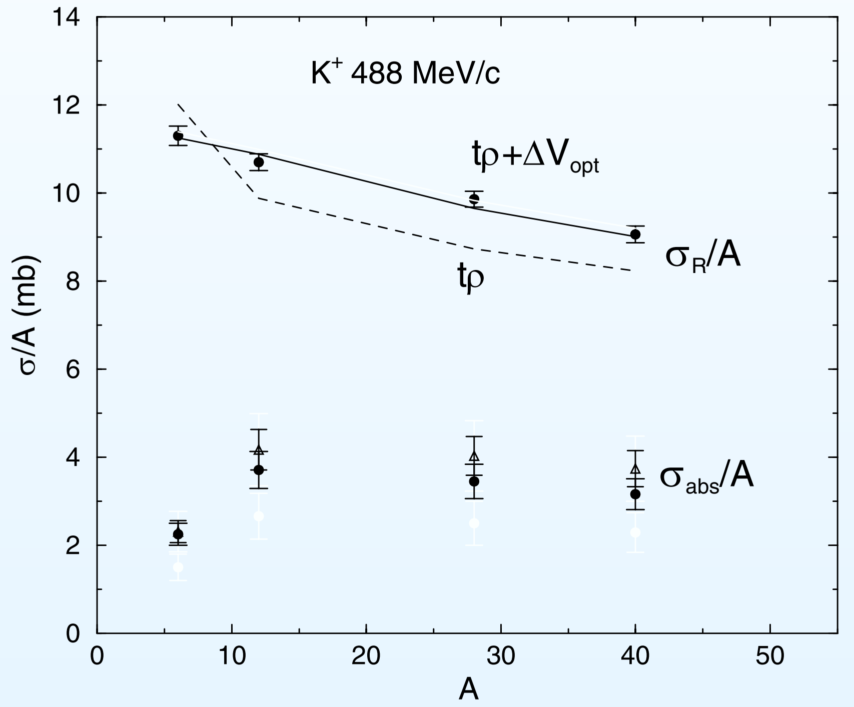
Gibbs et al (84), Brown et al (88), Jiang et al (92), Oset et al (95)

A long-standing problem

Recent analysis of the data by A. Gal and E. Friedman

Phys. Rev. Lett. 94, 072301 (2005)

- improved fits with two-body absorption
  - $\Pi_K(q,\rho) \simeq T\rho + b\,\rho^2$
- Absorption cross sections per nucleon of ≈ 3.5 mb



The underlying microscopic process could involve the excitation of Θ^+ ! ($K^+ nN \to \Theta^+ N$)

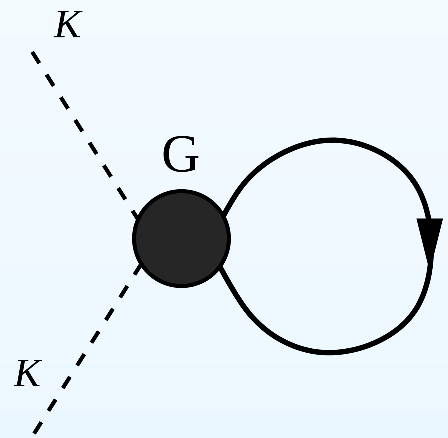
$T\rho$ vs $G-$matrix. Selfconsistency

Effective KN interaction and K selfenergy ($G-$matrix approach)

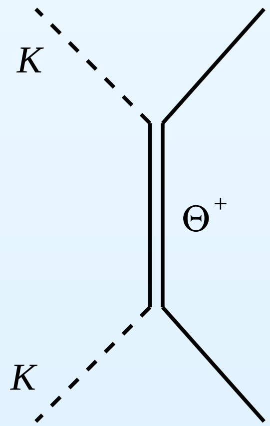
$$G_{KN}(\Omega) = V_{KN}(\sqrt{s}) + V_{KN}(\sqrt{s})\,\frac{Q_{KN}}{\Omega - E_K - E_N + i\eta}\,G_{KN}(\Omega)$$

- $E_K(\vec{q};\rho) = \sqrt{m_K^2 + \vec{q}^{\,2}} + \mathrm{Re}\, U_K(E_K, \vec{q};\rho)$
- $U_K(E_K, \vec{q};\rho) = \sum_{N \lesssim F} G_{KN}(\Omega = E_N + E_K)$
  $(\Pi_K = 2E_K U_K)$

$(E_N \approx -80$ MeV at $\rho = \rho_0)$



$V \longrightarrow$ meson exchange Jülich interaction + Θ^+ pole term
J. Haidenbauer, G. Krein, Phys. Rev. C48, 052201 (2003)
(Bare coupling and mass to reproduce $M^{phys}_{\Theta^+}$, $\Gamma = 5$ MeV
in free space KN amplitude)

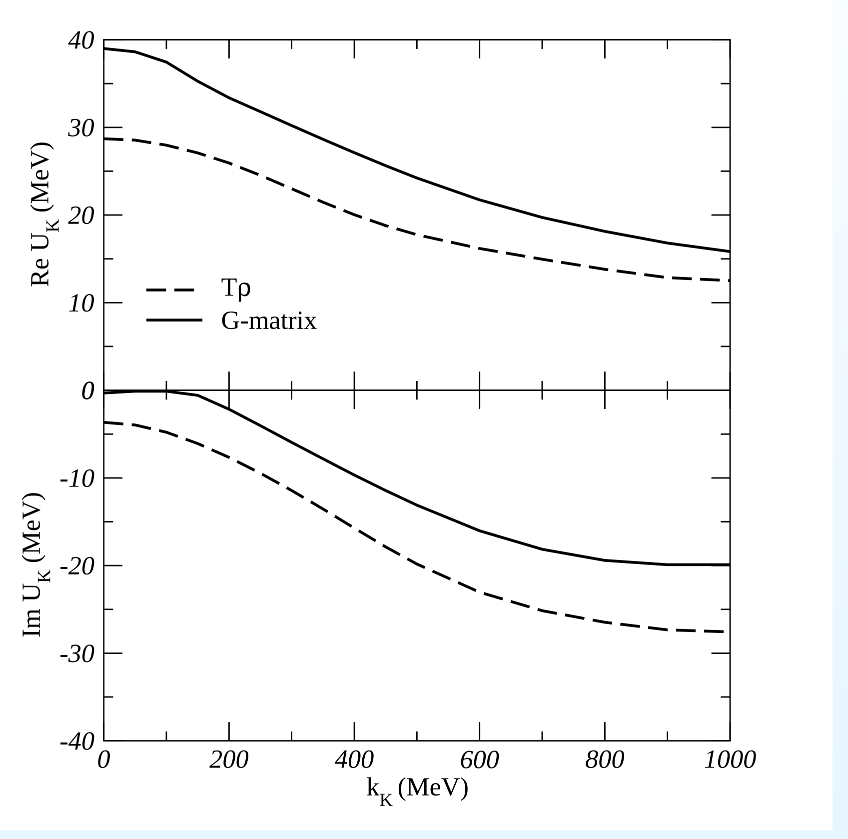


$T\rho$ vs $G-$matrix. Selfconsistency

- $T\rho$: ignores medium effects on KN interaction and K, N potentials
- $G-$matrix:
  - *less repulsive* at $\vec{k}=0$
  - Pauli blocking prevents scattering with N below the Fermi momentum

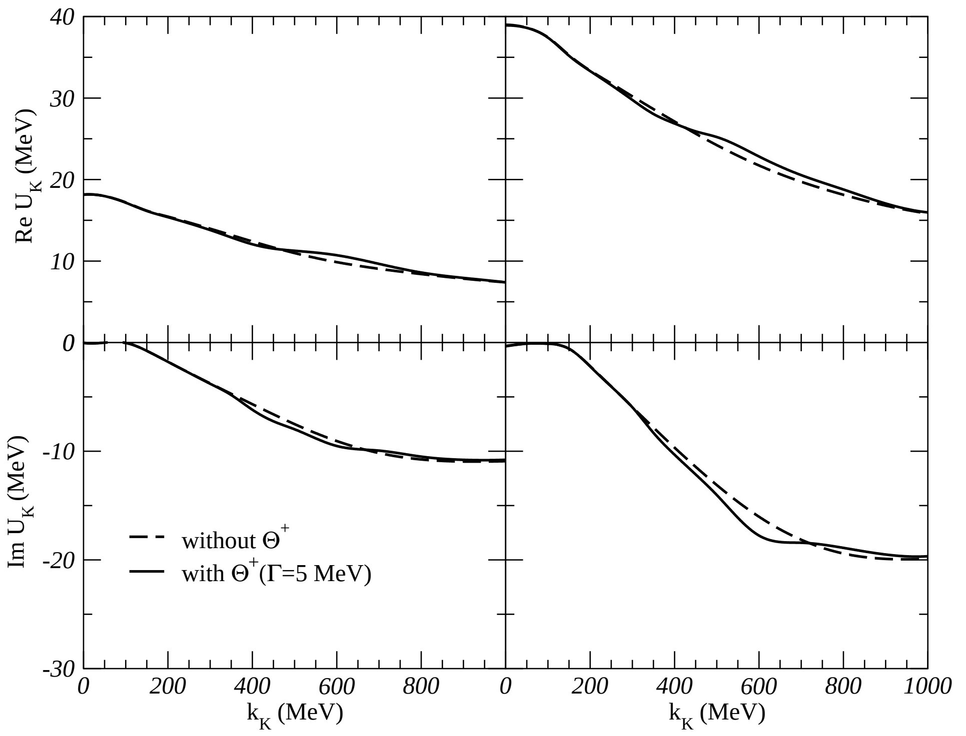
C.L. Korpa, M.F.M. Lutz,
Acta Phys. Hung. A22, 21 (2005)

based on vacuum KN scattering amplitudes



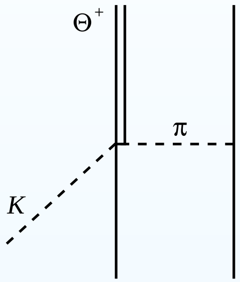
$\longrightarrow$ *Medium effects + selfconsistency* relevant for KN interaction (not so "featureless")

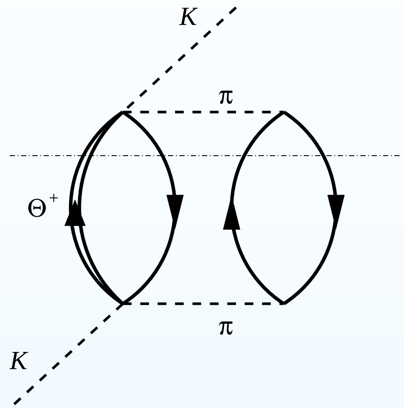
Effect of the Pentaquark ($KN \rightarrow \Theta^+$)



- The one-body mechanism is almost irrelevant
- Tied to the small $KN\Theta^+$ couping

Kaon two-body absorption ($KNN \rightarrow \Theta^+$ N)

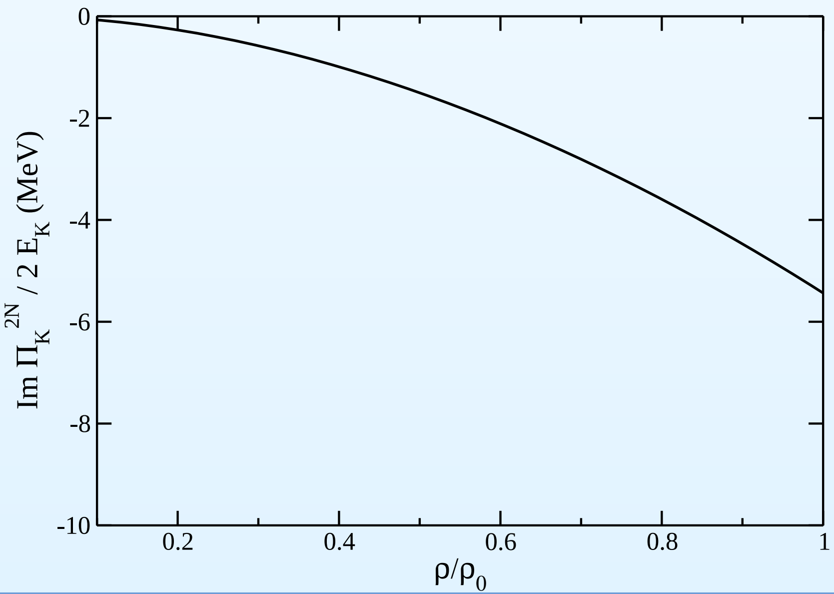




- $\Pi_K^{2N}(q^0, \vec{q}; \rho) = i \int \frac{d^4k}{(2\pi)^4} \left[D_\pi^{(0)}(k) \right]^2 \Pi_\pi(k; \rho)\, \tilde{U}_\Theta(q, k; \rho)$
- $\tilde{U}_\Theta(q, k; \rho) \simeq -9 \sum_{j=S,V} |\, t^{(j)}(k, q)\, |^2\, U_\Theta(q - k; \rho)$

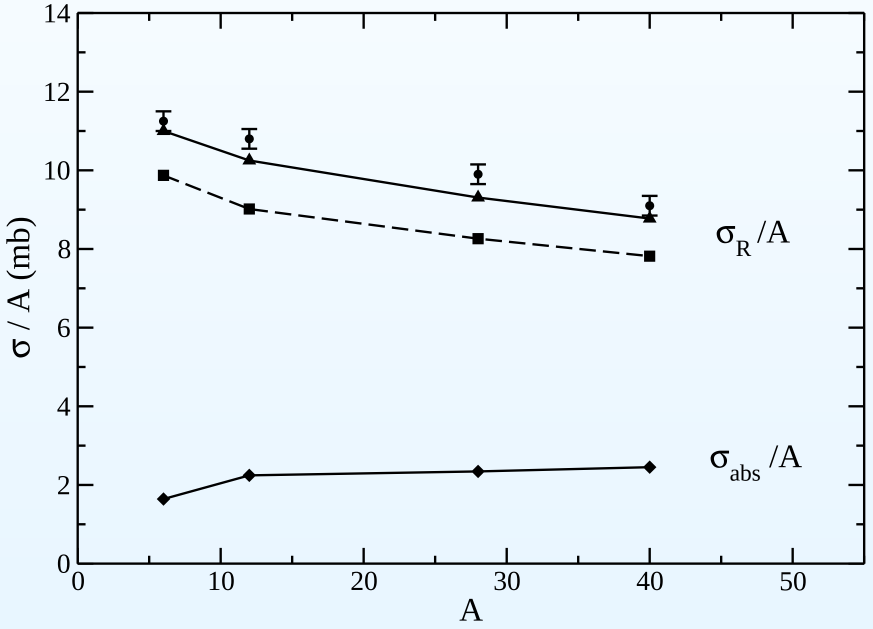
Pion selfenergy:
$p - h$, $\Delta - h$,
short range correlations (g')

Sizeable contribution, clear
$\mathcal{O}(\rho^2)$ dependence ($k \sim 500$ MeV)



K nucleus cross section

- Eikonal approximation for the cross sections (sensible for incident kaon momentum 488 MeV)
- Local density approximation + realistic nuclear Fermi distributions (3pF)



- The kaon potential with $KN \to \Theta^+$ underestimates data by 10-20 %
- Absorption cross sections per nucleon of $2-3$ mb
  A. Gal, E. Friedman, Phys. Rev. Lett. 94, 072301 (2005)
- σ_R/A with the total kaon potential $\to$ very close to experimental data

Summary

Θ^+ selfenergy

- We have evaluated the selfenergy of the Θ^+ in the nuclear medium associated to the KN and the MMB decay channels.
- The potential associated to the KN decay is small, even assuming a large free width of around 15 MeV for the Θ^+ (Pauli blocking and small phase space from Θ^+ binding)
- We fi nd a large attractive Θ^+ potential in the nucleus associated to the two meson cloud of the antidecuplet.
- A new decay channel opens for the Θ^+ in the medium, $\Theta^+ N \to NNK$.
- The width from this channel, together with the one from KN decay, is still small compared to the separation of the bound levels of the Θ^+ in light and intermediate nuclei.

Summary

- This opens the possibility of the existence of Θ^+ hypernuclei *BUT!*

In reaching the former conclusions there are several assumptions done.

1. The Θ^+ is assumed to be $1/2^+$ associated to an $SU(3)$ antidecuplet;
2. The $N^*(1710)$ is supposed to couple largely to this antidecuplet;
3. Some values of the cut off have been chosen to obtain reasonable numbers for the free Θ^+ selfenergy;
4. The $N^*(1710)$ width and the partial decay ratios, used to obtain the coupling constants, have large experimental uncertainties.

- With all these assumptions one must accept a large uncertainty in the results. However, the order of magnitude for the potential, even with a wide margin of uncertainty, claims for a possibility of bound state formation.

(K^+, π^+) reaction, *H. Nagahiro* et al, *Phys. Lett. B620, 125 (2005)*

Summary

Kaon optical potential

- Selfconsistent calculation of the K optical potential in symmetric nuclear matter from Jülich KN + Θ^+ pole term.
- Selfconsistency leads to non-trivial effects as compared to standard $T\rho$ approximation.
- $KN \to \Theta^+$ mechanism negligible due to small Θ^+KN coupling.
- $KNN \to \Theta^+N$ mechanism significantly contributes to Im V_K
- Nuclear absorption cross sections of $2-3$ mb per nucleon.
- Reaction cross sections increased by $10-15$ %, very close to experimental data.

D. Cabrera, Q.B. Li, V.K. Magas, E. Oset, M.J. Vicente Vacas, Phys. Lett. B608 (2005) 231

L. Tolos, D. Cabrera, A. Ramos, A. Polls, accepted for publication in Phys. Lett. B

Cross section formulae

Absorption cross section (for a given kaon momentum):

$$\sigma_A = \int d^2b \left(1 - \exp\left[-\int_{-\infty}^{\infty} -\frac{1}{q}\,\mathrm{Im}\,\Pi_K^A(\rho(\vec{b},z))\,dz\right]\right)$$

"Probability that a kaon is absorbed when crossing the nucleus along the z direction"
or, alternatively,

$$\sigma_A = \int d^2b\,dz\,\exp\left(-\int_{-\infty}^{z} -\frac{1}{q}\,\mathrm{Im}\,\Pi_K^A(\rho(\vec{b},z'))\,dz'\right)\left[-\frac{1}{q}\,\mathrm{Im}\,\Pi_K^A(\rho(\vec{b},z))\right]$$

"Probability that a kaon reaches the point z without being absorbed ("shadowing"), times the probability that the kaon is absorbed in z"

$\longrightarrow$ Quasielastic interactions can be considered in Π_K^A by using the full potential (overestimates the shadowing of the kaons)

$[-\frac{1}{q}\,\mathrm{Im}\,\Pi_K^A] \longrightarrow$ absorption probability per unit length

Coupling to $K^*(892)$

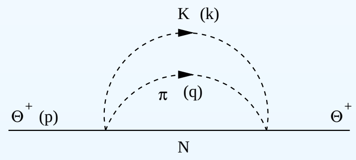
G.A. Miller, Phys. Rev. C70, 022202 (2004)

S.I. Nam, A. Hosaka, H.C. Kim, hep-ph/0505134; hep-ph/0508210

Some authors suggest a strong $K^* N \Theta^+$ coupling could lead to a sizable attraction in the nuclear medium.

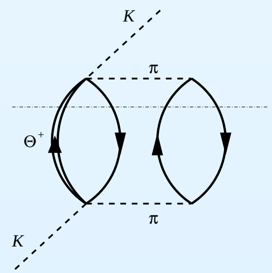
Also proposed as a possible mechanism for Θ^+ photoproduction ($\gamma N \to \bar{K}\Theta^+$, $\gamma N \to \bar{K^*}\Theta^+$)

In our model, it is partly taken into account in the two-meson (vector) coupling ($K\pi N\Theta^+$), since the two-meson cloud reconstructs a K^* meson



$$
\begin{aligned}
|t^V|^2 &= \left(\frac{g}{4f^2}\right)^2 \frac{1}{2M} \{[E_N(\vec{k}+\vec{q})+M][\omega_1(k)-\omega_2(q)]^2 \\
&\quad + 2(\vec{k}^{\,2}-\vec{q}^{\,2})[\omega_1(k)-\omega_2(q)] + [E_N(\vec{k}+\vec{q})-M](\vec{k}-\vec{q})^2\} \left|\frac{m_{K*}^2}{(q+k)^2-m_{K*}^2}\right|^2
\end{aligned}
$$

$$
\begin{aligned}
|\, t^V \,|^2 &= -\left(\frac{g}{4f^2}\right)^2 \left[\left(1+\frac{M_\Theta}{E_\Theta(\vec{q}-\vec{k}\,)}\right)(k^0+q^0)^2 + \frac{2}{E_\Theta(\vec{q}-\vec{k}\,)}(\vec{k}^2-\vec{q}^{\,2})(k^0+q^0) + \right. \\
&\quad \left.\left(1-\frac{M_\Theta}{E_\Theta(\vec{q}-\vec{k}\,)}\right)(\vec{k}+\vec{q}\,)^2\right] \left|\frac{m_{K*}^2}{(q-k)^2-m_{K*}^2}\right|^2
\end{aligned}
$$



Outlook

- Careful error analysis to study the uncertainties of the model and its effect on the kaon potential and the K nucleus cross sections
- Selfconsistency at the level of the Θ^+ medium effects:
  - Large attractive selfenergy should be considered in the two-body mechanism, though it will largely compensate with the nucleon attraction.
  - Same should be considered in the one-body contribution, whose effect would be shifted down in energy (negligible anyway)
- Selfconsistency at the level of the kaon selfenergy.
- Tests of the K ($\bar{K}$) potential:
  - ϕ meson properties in nuclear medium; $A-$dependence of ϕ meson nuclear photoproduction
  - κ meson ($K\pi$) properties in nuclear medium
  - Theoretical tools: Energy-weighted sum rules for mesonic in-medium spectral functions