$\bar{K}^*$ meson in dense matter

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Outline

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3. $\bar{K}^* \to \bar{K}\pi$ in dense matter
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6. Conclusions

Previous results on the interaction of vector mesons with nuclear matter

- Within the Nambu Jona Lasinio model there is no shift of the vector masses while the σ-mass decreases sharply with the density. V. Bernard and U. G. Meissner, Nucl. Phys. A **489**, 647 (1988).
- Recent calculations show no shift of the ρ meson and a broadening of the vector meson in nuclear matter. Rapp, 97; Urban, 99; D. Cabrera, E. Oset and M. J. Vicente Vacas, Nucl. Phys. A **705**, 90 (2002):

$$\triangle M(\rho_0) \sim 30 \text{ MeV}, \ \Gamma(\rho_0) \sim 200 \text{ MeV}.$$

- In the case of the ϕ meson, theoretical calculations also show no shift of the mass and a broadening of the meson. D. Cabrera and M. J. Vicente Vacas, Phys. Rev. C **67**, 045203 (2003):

$$\triangle M(\rho_0) \sim 8 \text{ MeV}, \ \Gamma(\rho_0) \sim 30 \text{ MeV}.$$

- The case of the ω meson had been more controvelsial [1,2,3,4,5].

1. M. Post, S. Leupold and U. Mosel, Nucl. Phys. A **741**, 81 (2004)
2. M. Kaskulov, H. Nagahiro, S. Hirenzaki and E. Oset, Phys. Rev. C **75**, 064616 (2007)
3. D. Trnka *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **94**, 192303 (2005)
4. Mariana Nanova, Talk given at the XIII International Conference on Hadron Spectroscopy, December 2009, Florida State University.
5. M. Kotulla *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 192302 (2008)

Previous results on the interaction of vector mesons with nuclear matter

- In M. Kaskulov, E. Hernandez and E. Oset, Eur. Phys. J. A **31**, 245 (2007) the authors predict no shift and a width of $\Gamma(\rho_0) \sim 90$ MeV at normal nuclear density.
- Experiments done by the CLASS Collaboration confirms this null shift for the ρ mass and a broadening of the ρ, ω, ϕ mesons at normal nuclear density. M. H. Wood *et al.* [CLAS Collaboration], Phys. Rev. C **78**, 015201 (2008). C. Djalali *et al.*, Nucl. Part. Phys. **35**, 104035 (2008).
- These theoretical predictions and the results of CLASS are in contradiction with the parametrization derived by Hatsuda and Lee:

  $$m = m_0(1 - 0.16\frac{\rho}{\rho_0})$$

  and with the 20 % decrease in the ρ meson mass predicted by Brown and Rho.
- While the KEK team had earlier reported an attractive mass shift of the ρ. Conclusions could depend on the way the background is subtracted. R. Muto *et al.* [KEK-PS-E325 Collaboration], Phys. Rev. Lett. **98**, 042501 (2007)

The $VB \to VB$ interaction

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle$$

$$\mathcal{L}^{(3V)}_{III} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

$$\mathcal{L}^{(c)}_{III} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

$V_{\mu\nu}$, g

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$g = \frac{M_V}{2f}$$

V_μ

$$\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$

$$\mathcal{L}_{BBV} = \frac{g}{2}\left(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle\right)$$

1. Klingl,97; Palomar,02; M. Bando, T. Kugo, S. Uehara, K. Yamawaki, 1985, 88, 03
2. E. Oset and A. Ramos, arXiv:0905.0973 (2009, Eur. Phys. J. A)

The $VB \to VB$ interaction

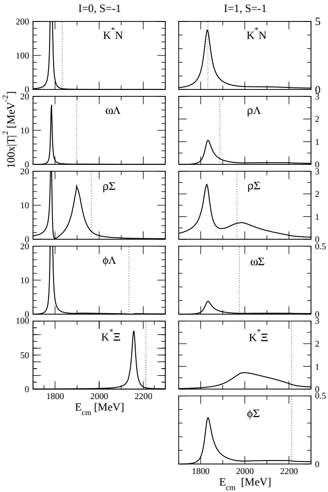


Figure: $|T|^2$ for different channels for $I = 0, 1$ and strangeness $S = -1$. Channel thresholds are indicated by vertical dotted lines. 3Λ and 2Σ appear: $\Lambda(1783)$, $\Lambda(1900)$, $\Lambda(2158)$ and $\Sigma(1830)$, $\Sigma(1987)$. PDG: $\Lambda(1800)$, $\Lambda(2000)$, $\Sigma(1750)$, $\Sigma(1940)$, $\Sigma(2000)$.

$\bar{K}^*$ self-energy from the s-wave $\bar{K}^*N$ interaction

Meson-baryon function loop in nuclear matter:

$$\begin{aligned} G^\rho(P) &= G^0(\sqrt{s}) + \lim_{\Lambda\to\infty}\delta G^\rho_\Lambda(P), \\ \delta G^\rho_\Lambda(P) &\equiv G^\rho_\Lambda(P) - G^0_\Lambda(\sqrt{s}) \\ &= i2M\int_\Lambda \frac{d^4q}{(2\pi)^4}\left(D^\rho_{\mathcal{B}}(P-q)\,D^\rho_{\mathcal{M}}(q) - D^0_{\mathcal{B}}(P-q)\,D^0_{\mathcal{M}}(q)\right) \end{aligned}$$

In-medium propagators:

$$\begin{aligned} D^\rho_N(p) &= \frac{2M_N}{2E_N(\vec{p}\,)}\left\{\left(\frac{1-n(\vec{p}\,)}{p^0 - E_N(\vec{p}\,) + i\varepsilon} + \frac{n(\vec{p}\,)}{p^0 - E_N(\vec{p}\,) - i\varepsilon}\right) u_r(\vec{p})\bar{u}_r(\vec{p}) + \frac{v_r(-\vec{p})\bar{v}_r(-\vec{p})}{p^0 + E_N(\vec{p}\,) - i\varepsilon}\right\} \\ &= D^0_N(p) \;+\; 2\pi i\, n(\vec{p}\,)\,\frac{\delta\left(p^0 - E_N(\vec{p}\,)\right)}{2E_N(\vec{p}\,)} \\ D^\rho_{\bar{K}^*}(q) &= \left((q^0)^2 - \omega(\vec{q})^2 - \Pi_{\bar{K}^*}(q)\right)^{-1} = \int_0^\infty d\omega\left(\frac{S_{\bar{K}^*}(\omega,\vec{q}\,)}{q^0-\omega+i\varepsilon} - \frac{S_{K^*}(\omega,\vec{q}\,)}{q^0+\omega-i\varepsilon}\right) \end{aligned}$$

$\bar{K}^*$ self-energy from the s-wave $\bar{K}^* N$ interaction

$$G^{\rho}{}_{\bar{K}^*N}(P) = G^0_{\bar{K}^*N}(\sqrt{s}) + \int \frac{d^3q}{(2\pi)^3} \frac{M_N}{E_N(\vec{p}\,)} \left[\frac{-n(\vec{p}\,)}{(P^0 - E_N(\vec{p}\,))^2 - \omega(\vec{q}\,)^2 + i\varepsilon} + (1 - n(\vec{p}\,)) \left(\frac{-1/(2\omega(\vec{q}\,))}{P^0 - E_N(\vec{p}\,) - \omega(\vec{q}\,) + i\varepsilon} + \int_0^\infty d\omega \, \frac{S_{\bar{K}^*}(\omega, \vec{q}\,)}{P^0 - E_N(\vec{p}\,) - \omega + i\varepsilon} \right) \right] \Bigg|_{\vec{p}=\vec{P}-\vec{q}}$$

$$T^{\rho\,(I)}(P) = \frac{1}{1 - V^I(\sqrt{s})\, G^{\rho\,(I)}(P)} V^I(\sqrt{s})$$

The in-medium $\bar{K}^*$ self-energy is then obtained by integrating $T^{\rho}{}_{\bar{K}^*N}$ over the nucleon Fermi sea,

$$\Pi_{\bar{K}^*}(q^0, \vec{q}\,) = \int \frac{d^3p}{(2\pi)^3} n(\vec{p}\,) \left[T^{\rho\,(I=0)}_{\bar{K}^*N}(P^0, \vec{P}) + 3T^{\rho\,(I=1)}_{\bar{K}^*N}(P^0, \vec{P}) \right]$$

$\bar{K}^*$ selfenergy coming from its decay into $\bar{K}\pi$

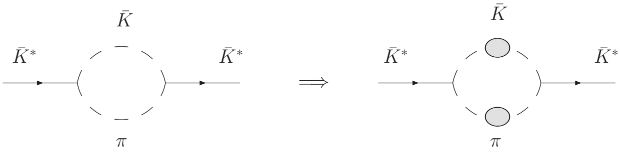


Figure: The $\bar{K}$ propagator in the free space (l), and in the medium (r).

In the free space, we have:

$$-i\Pi = -6g^2 \int \frac{d^4q}{(2\pi)^4} \frac{i}{q^2 - m_\pi^2} \frac{i}{(P-q)^2 - m_K^2 + i\epsilon} \epsilon'_\mu q^\mu \epsilon_\nu q^\nu$$

- For low momenta, $\frac{\vec{P}}{m_{K^*-}} \sim 0$, $\epsilon_\mu q^\mu \epsilon'_\nu q^\nu \longrightarrow \vec{\epsilon}\,' \cdot \vec{\epsilon}\, \frac{1}{3} \vec{q}\,^2\, \delta_{ij}$
- Cutkosky rules $\longrightarrow \mathrm{Im}\Pi = \frac{g^2}{4\pi} \vec{\epsilon} \cdot \vec{\epsilon}\,' q^3 \frac{1}{P^0} \longrightarrow \Gamma = 42$ MeV

$\bar{K}^*$ selfenergy coming from its decay into $\bar{K}\pi$

In the medium, we have:

$$\frac{1}{q^2 - m_\pi^2} \to \frac{1}{q^2 - m_\pi^2 - \Pi_\pi(q^0, \vec{q})}$$

$$\frac{1}{(P-q)^2 - m_K^2} \to \frac{1}{(P-q)^2 - m_K^2 - \Pi_K(P^0 - q^0, \vec{P} - \vec{q})}$$

We use their Lehmann representations, this is:

$$\begin{aligned} -i\Pi_{\bar{K}^*}(P^0, \vec{P}) &= 2\, g^2 \vec{\epsilon} \cdot \vec{\epsilon}\,' \int \frac{d^4 q}{(2\pi)^4} \vec{q}^{\,2} \int_0^\infty \frac{d\omega}{\pi} (-2\omega) \frac{\mathrm{Im} D_\pi(\omega, \vec{q})}{(q^0)^2 - \omega^2 + i\epsilon} \\ &\times \int_0^\infty \frac{d\omega'}{\pi} (-) \{ \frac{\mathrm{Im} D_{\bar{K}}(\omega', \vec{P} - \vec{q})}{P^0 - q^0 - \omega' + i\eta} - \frac{\mathrm{Im} D_K(\omega', \vec{P} - \vec{q})}{P^0 - q^0 + \omega' - i\eta} \} \end{aligned}$$

$\bar{K}^*$ selfenergy coming from its decay into $\bar{K}\pi$

- The real part of the free $\bar{K}^*$ selfenergy is subtracted to get its physical mass at $\rho = 0$
- The last term is $\propto \mathrm{Im} D_K$ is small and as approximation can be cancelled with the term in the free space

Therefore,

$$\Pi_{\bar{K}^*}(P^0, \vec{P}) =$$
$$2g^2 \epsilon \cdot \epsilon' \{ \int \frac{d^3q}{(2\pi)^3} \vec{q}^{\,2} \frac{1}{\pi^2} \int_0^\infty d\omega \, \mathrm{Im} D_\pi(\omega, \vec{q}) \int_0^\infty d\omega' \frac{\mathrm{Im} D_{\bar{K}}(\omega', \vec{P} - \vec{q})}{P^0 - \omega - \omega' + i\eta}$$
$$- \mathrm{Re} \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^{\,2}}{2\omega_\pi(q)} \frac{1}{2\omega_K(P-q)} \frac{1}{P^0 - \omega_\pi(q) - \omega_K(P-q) + i\epsilon} \}$$

$\bar{K}^*$ selfenergy coming from its decay into $\bar{K}\pi$

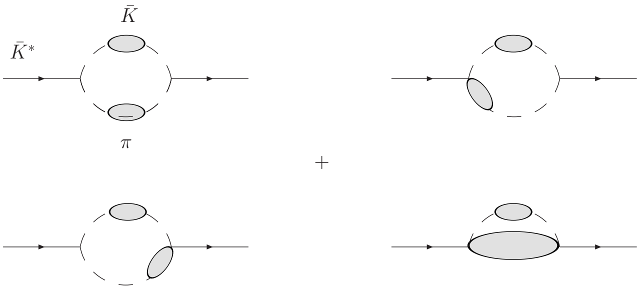
- The $\bar{K}$ selfenergy includes s and p waves that take into account the processes $\bar{K}N \to \bar{K}N$, $\bar{K}N \to \pi\Sigma$..., $\bar{K} \to \Lambda N^{-1}$, ΣN^{-1} and $\Sigma^* N^{-1}$ in the nuclear medium, Pauli-blocking, mean-field binding on the nucleons and hyperons and self-consistency.
- The π sefenergy incorporates a dominant p wave contribution that comes from ph and Δh excitations, $2p2h$ pieces and NN, $N\Delta$ short-range correlations by means of a single Landau-Migdal parameter (g').

1. A. Ramos and E. Oset, Nucl. Phys. A671,481 (2000)
2. E. Oset, P. Fernandez, L. L. Salcedo and R. Brockmann, Phys. Rept. 188, 79(1990)
3. Phys. Rept. 188, 79(1990),A. Ramos, E. Oset and L. L. Salcedo, Phys. Rev. C50,2314 (1994)

The $\bar{K}^*$ selfenergy accounts for the processes $\bar{K}^* N \to \bar{K}^* N$, $\bar{K}^* N \to \rho\Sigma$..., $\bar{K}^* \to \bar{K}\pi$ in the medium which allows new decay channels as $\bar{K}^* NN \to \Lambda(1405)N$ and includes Pauli-blocking, mean-field binding on the nucleons and self-consistency.

$\bar{K}^*$ selfenergy coming from its decay into $\bar{K}\pi$

- We also include vertex correcions in the selfenergy of the pion



$$\tilde{\Pi}^{(p)}\vec{q}^{\,2} \Longrightarrow \tilde{\Pi}^{(p)}(\vec{q}^{\,2} + D_0^{(\pi)-1}(q) + \frac{3}{4}\frac{D_0^{(\pi)-2}(q)}{\vec{q}^{\,2}})\ , \qquad (1)$$

Results

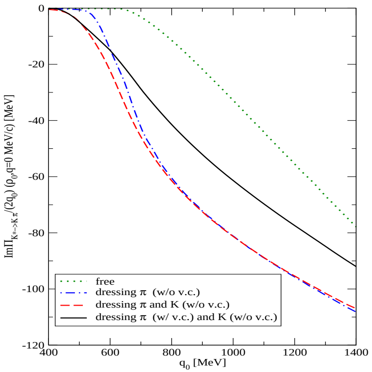
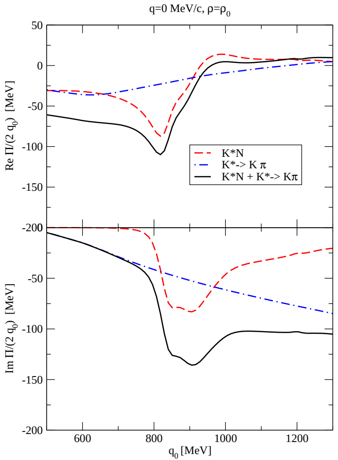


Figure: Imaginary part of the $\bar{K}^*$ self-energy at ρ_0 coming from the $\bar{K}\pi$ decay in dense matter.(i) calculation in free space, (ii) including the π self-energy, (iii) including the π and $\bar{K}$ self-energies, and (iv) including the π dressing with vertex corrections and the $\bar{K}$ self-energy.

Results

Figure: The $\bar{K}^*$ self-energy showing the different contributions:
(i) self-consistent calculation of the $\bar{K}^*N$ interaction,
(ii) self-energy coming from $\bar{K}^* \to \bar{K}\pi$ decay,
(iii) combined self-energy from both previous sources.



Results

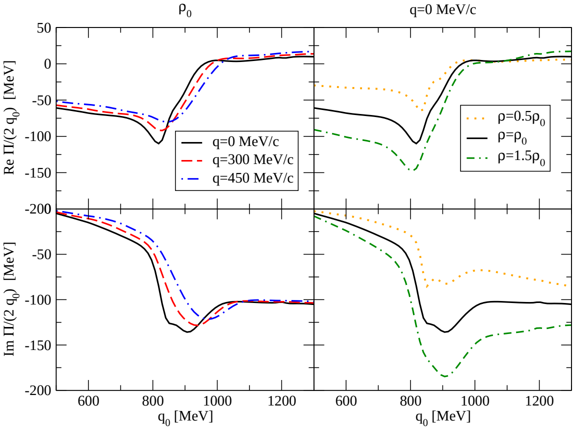
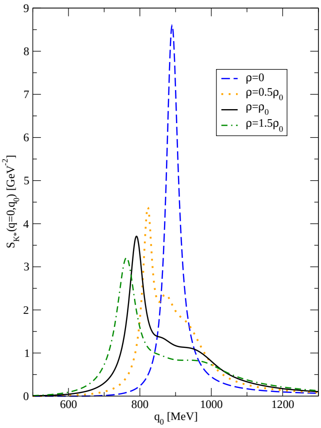


Figure: The $\bar{K}^*$ self-energy as a function of the meson energy q_0 for different momenta and densities.

Results



$$m - m^*(\rho = \rho_0) = 50\,\text{MeV}$$

$$\Gamma_0 = 50\,\text{MeV}$$

$$\Gamma(\rho = \rho_0) = 280\,\text{MeV}$$

Figure: The $\bar{K}^*$ spectral function for different densities.

Transparency ratio

Definition

$$\tilde{T}_A = \frac{\sigma_{\gamma A \to K^+ \; K^{*-} \; A'}}{A \sigma_{\gamma N \to K^+ \; K^{*-} \; N}}$$

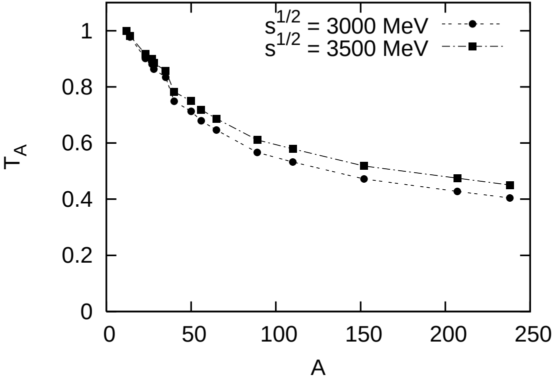
- Describes the loss of flux of K^{*-}-mesons in the nuclei and is related to its width in the medium
- In the Eikonal Approximation,

$$\tilde{T}_A \propto \exp\left[\int_0^\infty dl \frac{\mathrm{Im}\Pi_{K^{*-}}(\rho(\vec{r}\,'))}{|\vec{p}_{K^{*-}}|}\right] \quad \text{"Survival probability"}$$

Transparency ratio

- $^{12}_{6}$C, $^{14}_{7}$N, $^{23}_{11}$Na, $^{27}_{13}$Al, $^{28}_{14}$Si, $^{35}_{17}$Cl, $^{32}_{16}$S, $^{40}_{18}$Ar, $^{50}_{24}$Cr, $^{56}_{26}$Fe, $^{65}_{29}$Cu, $^{89}_{39}$Y, $^{110}_{48}$Cd, $^{152}_{62}$Sm, $^{207}_{82}$Pb, $^{238}_{92}$U

$$T_A = \frac{\tilde{T}_A}{\tilde{T}_{^{12}C}}$$



Conclusions

- We have studied the properties of $\bar{K}^*$ mesons in symmetric nuclear matter within a self-consistent coupled-channel unitary approach using hidden-gauge local symmetry.
- The corresponding in-medium solution incorporates Pauli blocking effects and the $\bar{K}^*$ meson self-energy self-consistently.
- We have found a small shift of the mass of the $\bar{K}^*$ resonance in the medium.
- We found that at $\rho = \rho_0$ the $\bar{K}^*$ width is increased to about 250 MeV, or about six times larger than its free width. This spectacular increase is much bigger than the one evaluated for the ρ meson in matter.
- We have made estimation of the transparency ratios in the $\gamma A \to K^+ \bar{K}^* A'$ reaction and found substantial reduction from unity of that magnitude which should be easier to observe experimentally by the CLASS collaboration.