ϕ Mesons in Dense and Strange Hadronic Matter

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ϕB Interactions

- Interaction with nucleons despite strange content.

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- KEK-325: ~ 14.5 MeV.

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Effective Chiral SU(3) Mean-field Model[1]

Features

1. Nucleon interactions are expressed in terms of scalar and vector fields σ, ζ, δ, χ, ω, ρ and ϕ.
2. Mean Field Approximation.
3. Basic QCD Properties.
   - Broken scale invariance (χ).
   - Spontaneous symmetry breaking.
   - Explicit symmetry breaking.
4. Study of density, temperature and magnetic field.

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Lagrangian Density

$$\mathcal{L}_{chiral} = \mathcal{L}_{kin} + \sum_{M=S,V} \mathcal{L}_{BM} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{ESB}.$$

Lagrangian Density

$$\mathcal{L}_{chiral} = \mathcal{L}_{kin} + \sum_{M=S,V} \mathcal{L}_{BM} + \mathcal{L}_{vec} + \mathcal{L}_{0} + \mathcal{L}_{ESB}.$$

$$\mathcal{L}_{\mathrm{BM}} = \mathcal{L}_{\mathrm{BS}} + \mathcal{L}_{\mathrm{BV}} = -\sum_i \bar{\psi}_i \left[m_i^* + g_{\omega i}\gamma_0 \omega + g_{\rho i}\gamma_0 \rho + g_{\phi i}\gamma_0 \phi \right] \psi_i ,$$

$$\mathcal{L}_{\mathrm{vec}} = g_4(\omega^4 + 6\omega^2\rho^2 + \rho^4 + 2\phi^4) + \frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2)\frac{\chi^2}{\chi_0^2},$$

$$\mathcal{L}_0 = -\frac{1}{2}k_0\chi^2(\sigma^2 + \zeta^2 + \delta^2) + k_2\left(\frac{\sigma^4}{2} + \zeta^4 + \frac{\delta^4}{2} + 3(\sigma\delta)^2\right) + k_1(\sigma^2 + \zeta^2 + \delta^2)^2$$
$$+ k_3\chi(\sigma^2 - \delta^2)\zeta - k_4\chi^4 - \frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} + \frac{d}{3}\chi^4 \ln\left(\frac{(\sigma^2 - \delta^2)\zeta}{\sigma_0^2\zeta_0}\left(\frac{\chi^3}{\chi_0^3}\right)\right),$$

$$\mathcal{L}_{\mathrm{ESB}} = -\frac{\chi^2}{\chi_0^2}\left[\frac{1}{2}m_\pi^2 f_\pi(\sigma + \delta) + \frac{1}{2}m_\pi^2 f_\pi(\sigma - \delta) + \left(\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right].$$

Thermopotential per unit volume at zero B

$$\frac{\Omega}{V} = -\frac{\gamma_i T}{(2\pi)^3} \sum_{i=p,n} \int d^3k \Big\{ \ln\left(1 + e^{-\beta[E_i^*(k) - \mu_i^*]}\right) + \ln\left(1 + e^{-\beta[E_i^*(k) + \mu_i^*]}\right) \Big\} - \mathcal{L}_{vec} - \mathcal{L}_0 - \mathcal{L}_{SB} - \mathcal{V}_{vac}.$$

Minimizing Thermopotential

$$\frac{\partial(\Omega/V)}{\partial\sigma} = k_0\chi^2\sigma - 4k_1\left(\sigma^2+\zeta^2+\delta^2\right)\sigma - 2k_2\left(\sigma^3+3\sigma\delta^2\right)$$

$$-2k_3\chi\sigma\zeta - \frac{d}{3}\chi^4\left(\frac{2\sigma}{\sigma^2-\delta^2}\right) + \left(\frac{\chi}{\chi_0}\right)^2 m_\pi^2 f_\pi - \sum g_{\sigma i}\rho_i^s = 0,$$

$$\frac{\partial(\Omega/V)}{\partial\zeta} = k_0\chi^2\zeta - 4k_1\left(\sigma^2+\zeta^2+\delta^2\right)\zeta - 4k_2\zeta^3 - k_3\chi\left(\sigma^2-\delta^2\right)$$

$$-\frac{d}{3}\frac{\chi^4}{\zeta} + \left(\frac{\chi}{\chi_0}\right)^2\left[\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right] - \sum g_{\zeta i}\rho_i^s = 0,$$

$$\frac{\partial(\Omega/V)}{\partial\delta} = k_0\chi^2\delta - 4k_1\left(\sigma^2+\zeta^2+\delta^2\right)\delta - 2k_2\left(\delta^3+3\sigma^2\delta\right)$$

$$+2k_3\chi\delta\zeta + \frac{2}{3}d\chi^4\left(\frac{\delta}{\sigma^2-\delta^2}\right) - \sum g_{\delta i}\tau_3\rho_i^s = 0,$$

$$\frac{\partial(\Omega/V)}{\partial\omega} = \left(\frac{\chi}{\chi_0}\right)^2 m_\omega^2\omega + g_4\left(4\omega^3+12\rho^2\omega\right) - \sum g_{\omega i}\rho_i^v = 0,$$

Minimizing Thermopotential...

$$\frac{\partial(\Omega/V)}{\partial\rho} = \left(\frac{\chi}{\chi_0}\right)^2 m_\rho^2\rho + g_4\left(4\rho^3 + 12\omega^2\rho\right) - \sum g_{\rho i}\tau_3\rho_i^v = 0,$$

$$\frac{\partial(\Omega/V)}{\partial\phi} = \left(\frac{\chi}{\chi_0}\right)^2 m_\phi^2\phi + 8g_4\phi^3 - \sum g_{\phi i}\rho_i^v = 0,$$

$$\frac{\partial(\Omega/V)}{\partial\chi} = k_0\chi\left(\sigma^2+\zeta^2+\delta^2\right) - k_3\left(\sigma^2-\delta^2\right)\zeta + \chi^3\left[1+\ln\left(\frac{\chi^4}{\chi_0^4}\right)\right]$$
$$+ (4k_4 - d)\chi^3 - \frac{4}{3}d\chi^3\ln\left(\left(\frac{\left(\sigma^2-\delta^2\right)\zeta}{\sigma_0^2\zeta_0}\right)\left(\frac{\chi}{\chi_0}\right)^3\right)$$
$$+ \frac{2\chi}{\chi_0^2}\left[m_\pi^2 f_\pi\sigma + \left(\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right] - \frac{\chi}{\chi^2{}_0}(m_\omega^2\omega^2 + m_\rho^2\rho^2) = 0,$$

Vector and Scalar Density of Nucleons

$$\rho_i^s = \gamma_i \int_0^{\mathbf{k}_{f,i}} \frac{d^3k}{(2\pi)^3} \frac{m_i^*}{E_i^*(k)} = \frac{\gamma_i m_i^*}{4\pi^2}\left[\mathbf{k}_{f,i} E_{f,i}^* - m_i^{*2} ln\left(\frac{\mathbf{k}_{f,i} + E_{f,i}^*}{m_i^*}\right)\right],$$

$$\rho_i^v = \gamma_i \int_0^{\mathbf{k}_{f,i}} \frac{d^3k}{(2\pi)^3} = \gamma_i \int_0^{\mathbf{k}_{f,i}} \frac{\mathbf{k}^2}{2\pi^2} dk = \frac{\gamma_i \mathbf{k}_{f,i}^3}{6\pi^2}.$$

Vector and Scalar Density of Nucleons

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Isospin Asymmetry

$$\eta = -\sum_i \frac{I_{3i}\rho_i^v}{2\rho_B},$$

where, $\rho_B = \sum_i \rho_i^v$ and $i = p, n, \Lambda, \Sigma^{\pm}, \Sigma^0, \Xi^-, \Xi^0$.

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Strangeness Fraction

$$f_s = \frac{\sum_i |s_i| \rho_i^v}{\rho_B},$$

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KB Interactions in Chiral SU(3) Model

$$
\begin{aligned}
\mathcal{L}_{\mathcal{KB}} = & -\frac{i}{4f_K^2}\Big[\Big(K^-(\partial_\mu K^+) - (\partial_\mu K^-)K^+\Big) \\
& \times \Big(2\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n - \bar{\Sigma^-}\gamma^\mu\Sigma^- + \bar{\Sigma^+}\gamma^\mu\Sigma^+ - 2\bar{\Xi^-}\gamma^\mu\Xi^- - \bar{\Xi^0}\gamma^\mu\Xi^0\Big) \\
& + \Big(\bar{K^0}(\partial_\mu K^0) - (\partial_\mu \bar{K^0})K^0\Big) \\
& \times \Big(\bar{p}\gamma^\mu p + 2\bar{n}\gamma^\mu n + \bar{\Sigma^-}\gamma^\mu\Sigma^- - \bar{\Sigma^+}\gamma^\mu\Sigma^+ - \bar{\Xi^-}\gamma^\mu\Xi^- - 2\bar{\Xi^0}\gamma^\mu\Xi^0\Big)\Big] \\
& + \frac{m_K^2}{2f_K}\Big[(K^+K^-)(\sigma + \sqrt{2}\zeta + \delta) + (K^0\bar{K^0})(\sigma + \sqrt{2}\zeta - \delta)\Big] \\
& - \frac{1}{f_K}\Big[(\partial_\mu K^+)(\partial^\mu K^-)(\sigma + \sqrt{2}\zeta + \delta) + (\partial_\mu K^0)(\partial^\mu \bar{K^0})(\sigma + \sqrt{2}\zeta - \delta)\Big] \\
& + \frac{d_1}{2f_K^2}\left((\partial_\mu K^+)(\partial^\mu K^-) + (\partial_\mu K^0)(\partial^\mu \bar{K^0})\right) \\
& \times \left(\bar{p}p + \bar{n}n + \bar{\Lambda^0}\Lambda^0 + \bar{\Sigma^+}\Sigma^+ + \bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^-}\Sigma^- + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0\right) \\
& + \frac{d_2}{2f_K^2}\Big[(\partial_\mu K^+)(\partial^\mu K^-)(\bar{p}p + \frac{5}{6}\bar{\Lambda^0}\Lambda^0 + \frac{1}{2}\bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^+}\Sigma^+ + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0) \\
& + (\partial_\mu K^0)(\partial^\mu \bar{K^0})(\bar{n}n + \frac{5}{6}\bar{\Lambda^0}\Lambda^0 + \frac{1}{2}\bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^-}\Sigma^- + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0)\Big],
\end{aligned}
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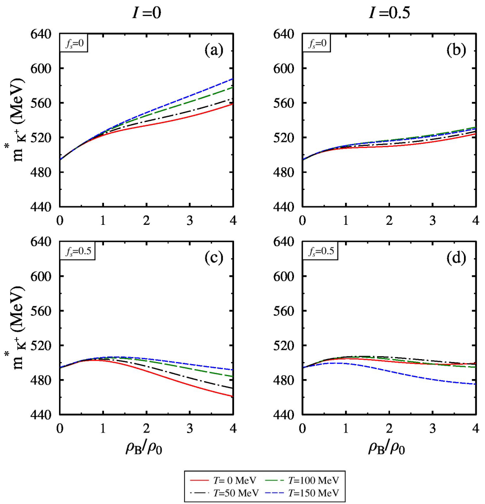
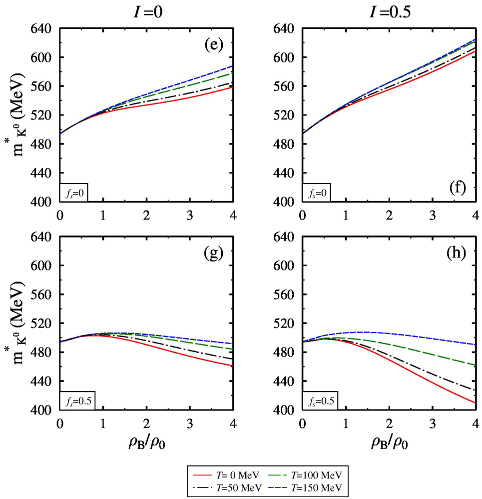
& + \Big(\bar{K^0}(\partial_\mu K^0) - (\partial_\mu\bar{K^0})K^0\Big) \\
& \times \Big(\bar{p}\gamma^\mu p + 2\bar{n}\gamma^\mu n + \bar{\Sigma^-}\gamma^\mu\Sigma^- - \bar{\Sigma^+}\gamma^\mu\Sigma^+ - \bar{\Xi^-}\gamma^\mu\Xi^- - 2\bar{\Xi^0}\gamma^\mu\Xi^0\Big)\Big] \\
& + \frac{m_K^2}{2f_K}\Big[(K^+K^-)(\sigma + \sqrt{2}\zeta + \delta) + (K^0\bar{K^0})(\sigma + \sqrt{2}\zeta - \delta)\Big] \\
& - \frac{1}{f_K}\Big[(\partial_\mu K^+)(\partial^\mu K^-)(\sigma + \sqrt{2}\zeta + \delta) + (\partial_\mu K^0)(\partial^\mu\bar{K^0})(\sigma + \sqrt{2}\zeta - \delta)\Big] \\
& + \frac{d_1}{2f_K^2}\left((\partial_\mu K^+)(\partial^\mu K^-) + (\partial_\mu K^0)(\partial^\mu\bar{K^0})\right) \\
& \times \left(\bar{p}p + \bar{n}n + \bar{\Lambda^0}\Lambda^0 + \bar{\Sigma^+}\Sigma^+ + \bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^-}\Sigma^- + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0\right) \\
& + \frac{d_2}{2f_K^2}\Big[(\partial_\mu K^+)(\partial^\mu K^-)(\bar{p}p + \frac{5}{6}\bar{\Lambda^0}\Lambda^0 + \frac{1}{2}\bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^+}\Sigma^+ + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0) \\
& + (\partial_\mu K^0)(\partial^\mu\bar{K^0})(\bar{n}n + \frac{5}{6}\bar{\Lambda^0}\Lambda^0 + \frac{1}{2}\bar{\Sigma^0}\Sigma^0 + \bar{\Sigma^-}\Sigma^- + \bar{\Xi^-}\Xi^- + \bar{\Xi^0}\Xi^0)\Big],
\end{aligned}
$$

$$-\omega^2 + \mathrm{k}^2 + m_K^2 - \Pi^*(\omega, |\mathrm{k}|) = 0.$$

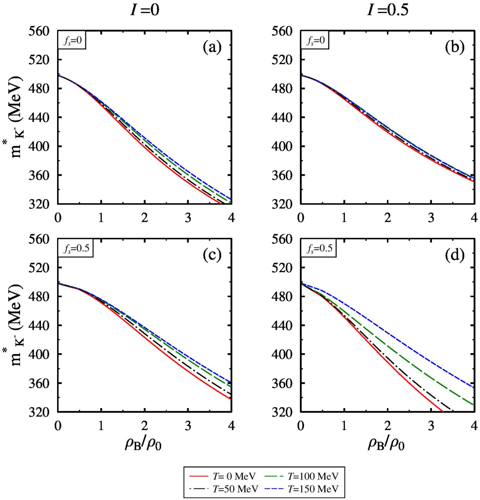
The in-medium mass of K^+ in the nuclear and hyperonic matter.



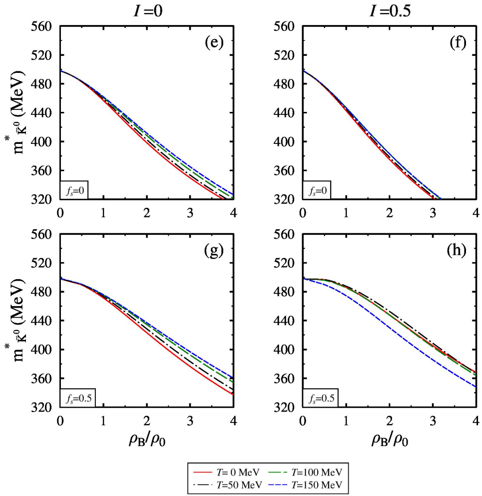
The in-medium mass of K^0 in the nuclear and hyperonic matter.



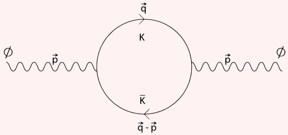
The in-medium mass of K^- in the nuclear and hyperonic matter.



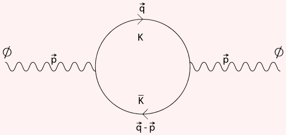
The in-medium mass of $\bar{K}^0$ in the nuclear and hyperonic matter.



In-medium ϕK Interactions



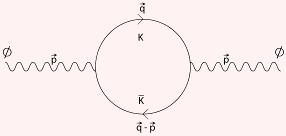
In-medium ϕK Interactions



ϕK Lagrangian with loop effect

$$\mathcal{L}_{\phi K \bar{K}} = i g_{\phi} \phi^{\mu} \left[\bar{K}(\partial_{\mu} K) - (\partial_{\mu} \bar{K}) K \right],$$

In-medium ϕK Interactions



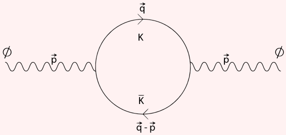
ϕK Lagrangian with loop effect

$$\mathcal{L}_{\phi K\bar{K}} = ig_{\phi}\phi^{\mu}\left[\bar{K}(\partial_{\mu}K) - (\partial_{\mu}\bar{K})K\right],$$

Self-energy of ϕ Meson

$$i\Pi^{*}_{\phi}(p) = -\frac{8}{3}g_{\phi}^{2}\int\frac{d^{4}q}{(2\pi)^{4}}\vec{q}^{\,2}D_{K}(q)D_{\bar{K}}(q-p),$$

In-medium ϕK Interactions



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Self-energy of ϕ Meson after Regularization

$$\Re\Pi^*_\phi = -\frac{4}{3} g_\phi^2 \, \mathcal{P} \int_0^{\Lambda_c} \frac{d^3 q}{(2\pi)^3} \vec{q}^{\,2} \left(\frac{\Lambda_c^2 + m_\phi^{*2}}{\Lambda_c^2 + 4 E_K^{*2}} \right)^4 \frac{(E_K^* + E_{\bar{K}}^*)}{E_K^* E_{\bar{K}}^* ((E_K^* + E_{\bar{K}}^*)^2 - m_\phi^{*2})}.$$

In-medium Mass and Decay Width of ϕ meson [1] [2]

ϕK Interactions...

with $E^*_K = (\vec{q}^{\,2} + {m^*_K}^2)^{1/2}$, $E^*_{\bar{K}} = (\vec{q}^{\,2} + {m^*_{\bar{K}}}^2)^{1/2}$, $m^*_K (= \frac{m^*_{K^+} + m^*_{K^0}}{2})$ and $m^*_{\bar{K}} (= \frac{m^*_{K^-} + m^*_{\bar{K}^0}}{2})$.

In-medium Mass and Decay Width of ϕ meson [1] [2]

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with $E^*_K = (\vec{q}^{\,2} + {m^*_K}^2)^{1/2}$, $E^*_{\bar{K}} = (\vec{q}^{\,2} + {m^*_{\bar{K}}}^2)^{1/2}$, $m^*_K (= \frac{m^*_{K^+} + m^*_{K^0}}{2})$ and $m^*_{\bar{K}} (= \frac{m^*_{K^-} + m^*_{\bar{K}^0}}{2})$.

In-medium Mass of ϕ Meson[1]

$$ {m^*_\phi}^2 = \left(m^0_\phi\right)^2 + \Re \Pi^*_\phi({m^*_\phi}^2), $$

In-medium Mass and Decay Width of ϕ meson [1] [2]

ϕK Interactions...

with $E_K^*=(\vec{q}^{\,2}+m_K^{*^2})^{1/2}$, $E_{\bar{K}}^*=(\vec{q}^{\,2}+m_{\bar{K}}^{*^2})^{1/2}$, $m_K^*(=\frac{m_{K^+}^*+m_{K^0}^*}{2})$ and $m_{\bar{K}}^*(=\frac{m_{K^-}^*+m_{\bar{K}^0}^*}{2})$.

In-medium Mass of ϕ Meson[1]

$$m_\phi^{*^2}=\left(m_\phi^0\right)^2+\Re\Pi_\phi^*(m_\phi^{*^2}),$$

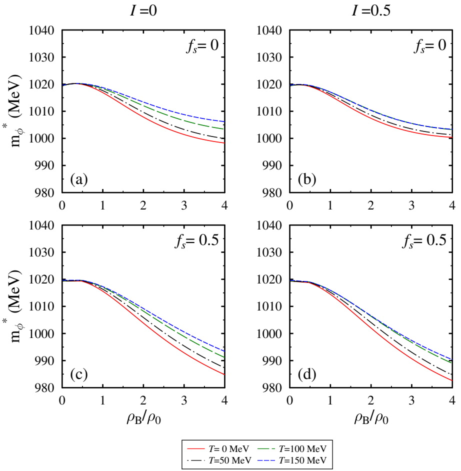
In-medium Decay Width of ϕ Meson[2]

$$\Gamma_\phi^*=\frac{g_\phi^2}{24\pi}\frac{1}{m_\phi^{*^5}}\left((m_\phi^{*^2}-(m_K^*+m_{\bar{K}}^*)^2)(m_\phi^{*^2}-(m_K^*-m_{\bar{K}}^*)^2)\right)^{3/2}.$$

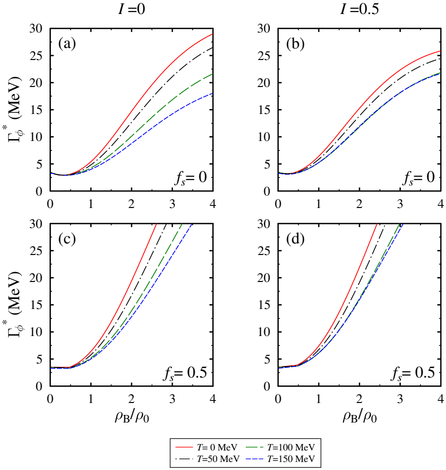
[1] J.J. Cobos-Martinez et al., Phys. Lett. B **771**, 113 (2017)

[2] G.Q. Li and C.M. Ko., Nucl. Phys. A **582**, 731 (1995).

The in-medium mass of the ϕ-meson in nuclear and hyperonic matter for the cut-off parameter $\Lambda_c = 3$ GeV.



The in-medium decay width of the $\phi \to K\bar{K}$ channel in the nuclear and hyperonic matter for $\Lambda_c = 3$ GeV.



Comparison with Existing Literature

Framework	m_ϕ^*(MeV)	Γ_ϕ^*(MeV)
This Work[a]	1017.6	4.8
QMC Model[b]	994	32.8
QCD Sum Rules[c]	1009	45
Chiral Perturbation Theory[d]	999	25

Table: In-medium mass and decay width at $\rho_B = \rho_0$.

[a] Rajesh Kumar and Arvind Kumar, Phys. Rev. C, **102** 045206 (2020).

[b] J.J. Cobos-Martinez *et al.*, Phys. Lett. B **771**, 113 (2017).

[c] F. Klingl, T. Waas and W. Weise, Phys. Lett. B **431**, 254 (1998).

[d] C. M. Ko et al., Phys. Rev. C **45**, 1400 (1992).

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Summary

- ϕ *Meson Mass and Decay Width in Strange Hadronic Matter.*
    - The mass of antikaons decreases more appreciably than kaons in the medium.
    - Despite a significant drop in the K and $\bar{K}$ mass, we observed a small downward mass shift in the in-medium mass of ϕ-meson.
    - The decay width shows broadening and it decreases with the increase in the strange content of the medium.
- Medium modified attributes such as mass shift, decay width, and other experimental observables can be experimentally verified in **JPARC**, **CBM** and **PANDA** experiment in the future project FAIR at GSI.
- There is also a proposal at **JLab** (following the 12 GeV upgrade), to study the binding of Helium nuclei with ϕ and η meson.
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Thank You