Open strange meson $K_1^{\pm}$ in hot and dense nuclear matter

Rajesh Kumar
and
Dr Arvind Kumar

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To study the in-medium mass of K_1 meson, we start with effective chiral mean-field model.

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

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

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

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

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

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

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 (T=0)

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

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

Quark Condensates

$$\langle \bar{u}u \rangle = \left(\frac{\chi}{\chi_0}\right)^2 \left[\frac{m_\pi^2 f_\pi}{2} \frac{(\sigma + \delta)}{m_u}\right],$$

$$\langle \bar{s}s \rangle = \frac{\chi^2}{\chi_0^2 m_s} \left(\sqrt{2} m_K^2 f_K - m_\pi^2 f_\pi\right) \zeta.$$

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Gluon Condensates

$$G_0 = \frac{8}{9} \left[(1-d)\chi^4 + \left(\frac{\chi}{\chi_0} \right)^2 \left(m_\pi^2 f_\pi \sigma + (\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi) \zeta \right) \right],$$

QCD Sum Rules

Using operator product expansion (OPE), the current-current correlator up to dimension 6 can be written as [a]

$$\Pi(q^2) = B_0 Q^2 \ln \frac{Q^2}{\mu^2} + B_2 \ln \frac{Q^2}{\mu^2} - \frac{B_4}{Q^2} - \frac{B_6}{Q^4}, \tag{1}$$

with $Q^2 \equiv -q^2$, μ=1 GeV as renormalization scale and B_n as Borel coefficients. In the nuclear medium, the degeneracy of K_1^+ and K_1^- do not hold, consequently, the charge symmetry breaking leads to even and odd contributions from the correlator, given as

$$\Pi(q^2) = \Pi^e(q^2) + q_0 \Pi^o(q^2).$$

[a] T. Song, T. Hatsuda and S. H. Lee, Physics Letters B **792**, 160 (2019).

QCD Sum Rules...

For small nuclear density (ρ_N), i.e., keeping only the linear terms in ρ_N, using Borel transformation the correlator can be expressed as

$$O(M^2)O'_{\pm} + M(M^2)m'_{\pm} + S(M^2){s'}_0^{\pm} = C_{\pm}(M^2),$$

with

$$O(M^2) = -m_{K_1}^2 e^{-m_{K_1}^2/M^2}, \quad M(M^2) = O_{K_1} m_{K_1}\left(-\frac{3}{2} + \frac{2m_{K_1}^2}{M^2}\right)e^{-m_{K_1}^2/M^2},$$

$$S(M^2) = \frac{1}{2}\left(1 + \frac{m_{K_1}}{\sqrt{s_0}}\right)(B_0 s_0 - B_2)e^{-s_0/M^2}, \quad C_{\pm}(M^2) = -m_s\langle\bar{u}u\rangle_N + \frac{\alpha_s}{12\pi}\langle G^2\rangle_N$$

$$+ \frac{m_N}{2}(A_2^u + A_2^s) \pm \frac{m_{K_1}}{3}(A_1^u - A_1^s) + \frac{32\pi\alpha_s}{9M^2}\Big\{\langle\bar{u}u\rangle_N\langle\bar{s}s\rangle_0 + \langle\bar{u}u\rangle_0\langle\bar{s}s\rangle_N + \frac{2}{9}(\langle\bar{u}u\rangle_N\langle\bar{u}u\rangle_0$$

$$+ \langle\bar{s}s\rangle_N\langle\bar{s}s\rangle_0)\Big\} - \frac{5m_N^3}{6M^2}(A_4^u + A_4^s) \mp \frac{2m_{K_1}m_N^2}{3M^2}(A_3^u - A_3^s) + m'_{\mp}\left\{\frac{O_{K_1}m_{K_1}}{2}e^{-m_{K_1}^2/M^2}\right\}$$

$$+ {s'}_0^{\mp}\left\{\frac{1}{2}\left(-1 + \frac{m_{K_1}}{\sqrt{s_0}}\right)(B_0 s_0 - B_2)e^{-s_0/M^2}\right\}.$$

QCD Sum Rules...

The in-medium mass ($m^*_\pm$), overlapping strength ($O^*_\pm$) and threshold parameter ($s_0^{\pm *}$) of $K_1^\pm$ mesons can be expressed via relations

$$O^*_\pm = O_{K_1} + \Delta O^*_{K_1^\pm} = O_{K_1} + O'_\pm \rho_N,$$

$$m^*_\pm = O_{K_1} + \Delta m^*_{K_1^\pm} = m_{K_1} + m'_\pm \rho_N,$$

$$s_0^{\pm^*} = s_0 + \Delta s_0^{*\pm} = s_0 + {s'}_0^{\pm} \rho_N,$$

QCD Sum Rules...

The following six simultaneous linear equation for $O'_{\pm}, m'_{\pm}, s'^{\pm}_{0}$ are obtained

$$O'_{\pm}\int dM^2 F^2(M^2) + m'_{\pm}\int dM^2 O(M^2)M(M^2) + s'^{\pm}_{0}\int dM^2 O(M^2)S(M^2)$$
$$= \int dM^2 O(M^2)C_{\pm}(M^2),$$
$$O'_{\pm}\int dM^2 O(M^2)M(M^2) + m'_{\pm}\int dM^2 M^2(M^2) + s'^{\pm}_{0}\int dM^2 M(M^2)S(M^2)$$
$$= \int dM^2 M(M^2)C_{\pm}(M^2),$$
$$O'_{\pm}\int dM^2 O(M^2)S(M^2) + m'_{\pm}\int dM^2 M(M^2)S(M^2) + s'^{\pm}_{0}\int dM^2 S^2(M^2)$$
$$= \int dM^2 S(M^2)C_{\pm}(M^2),$$

$K_1^{\pm}$ meson

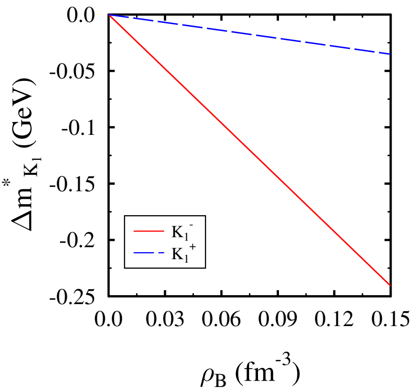

Figure: In-medium mass shift of K_1^+ and K_1^- meson.

Table: In-medium values of shift in overlapping strength $\Delta O^*_{K_1^\pm}$ (GeV^2), mass $\Delta m^*_{K_1^\pm}$ (GeV), and, threshold parameter $\Delta s_0^{*\pm}$ (GeV^2) at ρ_N=0.16 fm^{-3}, T=0 MeV.

	$\Delta O^*_{K_1^-}$	$\Delta m^*_{K_1^-}$	Δs_0^{*-}	$\Delta O^*_{K_1^+}$	$\Delta m^*_{K_1^+}$	Δs_0^{*+}
This work	-2.88$\times 10^{-2}$	-0.256	-1.28	-2.8$\times 10^{-3}$	-0.0374	-0.247
QCD sum rules [1]	-3.09$\times 10^{-2}$	-0.249	-1.25	-2.72$\times 10^{-3}$	-0.0348	-0.234

[1] T. Song, T. Hatsuda and S. H. Lee, Physics Letters B **792**, 160 (2019).

Summary and Outlook

- In-medium mass of K_1^- meson decreases significantly in the nuclear medium.
- Charge symmetry does not hold in the nuclear medium.
- The mass shift of K_1^- can be experimentally anticipated from the hadronic decays $K_1 \to K\rho$ and $K_1 \to K^*\pi$ as well as excitation function[a].
- The in-medium $K_1 N$ properties can also be studied through the K_1^- interactions with several nuclei at J-PARC[a].

[a] T. Song, T. Hatsuda and S. H. Lee, Physics Letters B **792**, 160 (2019).

Thank You