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Open strange mesons in (magnetized) nuclear matter

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Summary. — We investigate the mass modifications of open strange mesons (vector K^* and axial vector K_1) in isospin asymmetric nuclear matter using quantum chromodynamics sum rule (QCDSR) approach. The in-medium decay widths of $K^* \to K\pi$ and $K_1 \to K^*\pi$ are studied from the mass modifications of K_1, K^* and K mesons, using a light quark-antiquark pair creation model, namely the $^3P_0$ model. The in-medium decay width for $K_1 \to K^*\pi$ is compared with the decay widths calculated using a phenomenological Lagrangian. The effects of magnetic fields are also studied on mass and partial decay width of vector K^* meson decaying to $K\pi$.

1. – Introduction

The study of strange mesons has been the center of attention due to their significance in studying their yield and spectra, produced in HIC experiments as well as in the study of certain astronomical bodies, where strange matter could exist in the interior of neutron stars. The strange mesons (K, K^*, and ϕ) masses have been investigated in strong magnetic fields in ref. [1] due to $\phi - \eta'$ and $K^* - K$ mixing, and the decay widths $\phi \to K\bar{K}$, $K^* \to K\pi$ are studied in a field theoretic model for composite hadrons from the mass modifications of the mesons. The in-medium spectral functions and production cross-sections for the strange mesons ($K^*, \bar{K}^*$, and ϕ), in strange hadronic medium, have also been studied from their in-medium masses and decay widths [2]. The properties of vector $\bar{K}^*$ meson in the nuclear matter are investigated in ref. [3] using a unitary approach in coupled channels. The axial vector K_1 meson masses have been analyzed in the QCD sum rule analysis [4] in the nuclear matter and the decay widths for $K_1 \to K\pi\pi$ channel have been studied using the $^3P_0$ model [5]. The study of medium density effects might find relevance in future experiments at the GSI Facility for Antiproton and Ion Research (FAIR) and Nuclotron-based Ion Collider facility (NICA) [6, 7], where matter having large baryon density will be produced. Furthermore, the estimation of strong magnetic field production in the peripheral HIC experiments [8, 9] has raised immense interest in the study of the magnetic field effects on the produced medium. The effects of strong magnetic field on the K^* meson masses are found to be quite appreciable. This should have observable consequences on the production and decay of open strange K^* meson. The strong magnetic field effects on the K^* masses and decay widths (to $K\pi$) are studied at nuclear matter saturation density, ρ_0.

2. – QCD sum rule approach

In QCDSR approach, the spectral density of the current-current correlator function $\Pi^V(q^2 = -Q^2)$ on the phenomenological side is related with the QCD operator product expansion (OPE) side via a dispersion relation V [4,10,11]. The finite energy sum rules (FESRs) for the K^* meson in the presence of nuclear medium are given by

$$F^*_{K^*} = d_{K^*}(c_0^{K^*} s_0^{*K^*} + c_1^{K^*}), \tag{1}$$

$$F^*_{K^*} m^{*2}_{K^*} = d_{K^*}\left(\frac{(s_0^{*K^*})^2 c_0^{K^*}}{2} - c_2^{*K^*}\right), \tag{2}$$

$$F^*_{K^*} m^{*4}_{K^*} = d_{K^*}\left(\frac{(s_0^{*K^*})^3 c_0^{K^*}}{3} + c_3^{*K^*}\right), \tag{3}$$

with $d_{K^*} = 3$. These are solved to find the in-medium scale $s_0^{*K^*}$, overlap strength $F^*_{K^*}$ and mass $m^*_{K^*}$ of the vector meson. The $c_i^{K^*}$'s are the coefficients of expansion on the OPE side. The $c_0^{K^*}$ is the coefficient of leading order term in perturbative QCD. The $c_i^{K^*}(i = 1, 2, 3)$ coefficients provide the information about the non-perturbative effects of QCD as well as about the Wilson coefficients [4,12]. For the K^{*+} meson [4,13],

$$c_0^{K^*} = 1 + \frac{\alpha_s(Q^2)}{\pi}, \; c_1^{K^*} = -3(m_u^2 + m_s^2), \tag{4}$$

$$c_2^{K^*} = \frac{\pi^2}{3}\left\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu}\right\rangle + \frac{16\pi^2}{d_{K^*}}\langle m_u \bar{s}s + m_s \bar{u}u\rangle - \frac{4\pi^2}{d_{K^*}}\langle m_u \bar{u}u + m_s \bar{s}s\rangle, \tag{5}$$

$$c_3^{K^*} = -8\pi^3 \alpha_s \kappa_n \left[\frac{32}{9}\langle \bar{u}u\rangle\langle \bar{s}s\rangle + \frac{32}{81}\left(\langle \bar{u}u\rangle^2 + \langle \bar{s}s\rangle^2\right)\right], \tag{6}$$

where $\alpha_s(Q^2)$ is running coupling constant of QCD and (m_u, m_s) are current quark masses. The QCD scale $\Lambda_{QCD} = 140\,\text{MeV}$, with $b = 11 - (2/3)N_f$ with $N_f = 3$ as the number of quark flavors. However, for the K_1 meson, the spectral density $R^{K_1}_{\text{phen}}(s)$ will have a contribution from the pseudoscalar K meson as well as from the axial vector K_1 meson resonance [13,14] and the FESRs are modified accordingly [12].

3. – Effects of strong magnetic fields on K^* masses

3˙1. *Landau quantization.* – In the presence of external magnetic field, the energy levels of charged pseudoscalar (spin-0) and vector (spin-1) mesons are discretized to different Landau levels labelled as "n" [15]. The three polarization states ($S_z = +1, 0, -1$) of charged vector K^{*+} meson have different Landau contributions to the masses, and pseudoscalar K meson mass also gets modified due to Landau quantization.

3˙2. *Pseudoscalar-Vector (PV) meson mixing.* – The presence of external magnetic field can induce mixing between the pseudoscalar meson ($(S, S_z) = (0, 0)$) and longitudinal part ($(S, S_z) = (1, 0)$) of vector meson. The PV mixing effect can be incorporated through an effective interaction Lagrangian vertex [16,17] as well as through the spin-magnetic field interaction $(-\mu_i \cdot B)$ term [18,19]. The masses of the pseudoscalar (longitudinal part of vector) meson are observed to decrease (increase) as a result of PV mixing. The transverse polarized states, ($(S, S_z) = (1, +1)$ and $(1, -1)$), do not get mixed with any other states. However, the mass modifications of transverse polarized states can be studied through the spin-magnetic field interaction $(-\mu_i \cdot B)$ term.

4. – Decay widths of $K^* \to K\pi$ and $K_1 \to K^*\pi$

A) We study the decay width of vector ($K^* \to K\pi$) and axial vector ($K_1 \to K^*\pi$) meson, using the $^3P_0$ model [20, 21]. In this model, a light quark-antiquark pair is assumed to be produced in the $^3P_0$ state and the quark (antiquark) of this produced pair combines with the antiquark (quark) of the parent meson to give the final state mesons. The wave functions for the produced $\bar{q}q$ pair are chosen to be simple harmonic oscillator (SHO) wave functions. The decay width for the general decay $A \to BC$ is given by

$$\Gamma(A \to BC) = 2\pi \frac{p_B E_B E_C}{M_A} \sum_{LS} \left| \mathcal{M}_{LS} \right|^2, \tag{7}$$

where p_B is the 3-momentum of final state mesons in rest frame of initial meson and E_B, E_C are the energies of daughter particles. For the vector meson decay ($K^* \to K\pi$), the matrix element $\mathcal{M}_{LS}$ for the $1(^3S_1) \to 1(^1S_0) + 1(^1S_0)$ channel is given in refs. [12, 20, 21]. However, the axial vector $K_1(1270)$ meson is not a pure 1^3P_1 or 1^1P_1 state, but the physically observed $K_1(1270)$ and $K_1(1400)$ are a mixture of the two non-mass eigenstates, $\left|K_{1A}\right\rangle$ and $\left|K_{1B}\right\rangle$, of the two strange axial vector nonets 1^3P_1 and 1^1P_1, respectively [5, 22]. Therefore, the matrix element $\mathcal{M}_{LS}$ for the $K_1 \to K^*\pi$ decay gets contribution from both the 1^3P_1 and 1^1P_1 decay channels [12, 20].

B) We also use a phenomenological Lagrangian approach for the study of $K_1 \to K^*\pi$ decay width. The interaction Lagrangian is constructed from the anti-symmetric tensor fields for the axial-vector and vector meson. The decay width then is given as [23]

$$\Gamma_{K_1 \to K^*\pi} = \frac{|\lambda_{AVP}|^2}{2\pi M_{K_1}^2} q \left(1 + \frac{2}{3}\frac{q^2}{M_{K^*}^2}\right), \tag{8}$$

where q is the momentum of final state particles, given in the rest frame of initial meson. The coefficients λ_{AVP} of the interaction vertex are given in refs. [12, 23].

5. – Results and discussion

5·1. *In-medium masses using QCDSR approach.* – In fig. 1, the masses of K^* and K_1 mesons are plotted in subplots (a)–(d), as calculated within the QCDSR approach [12]. The masses are observed to decrease monotonically with an increase in the baryon density. This is because the chiral condensates $\langle \bar{q}q \rangle$ and the gluon condensates $\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu} \right\rangle$ decrease in magnitude as a function of baryon density. It is observed that there is a smaller mass drop in isospin asymmetric nuclear matter ($\eta \neq 0$) as compared to isospin symmetric matter ($\eta = 0$) for the charged K^{*+} and K_1^+ meson. The mass modifications for the neutral K^{*0} and K_1^0 mesons are observed to be smaller as compared to the corresponding charged mesons and the mass drop is observed to be slightly higher in $\eta \neq 0$ matter. Also, we observed a sharper mass drop for smaller values of nuclear medium density up to around $2\rho_0$. The drop in strange quark condensates decreases even more at higher densities, which results in smaller changes in K^* and K_1 meson mass at higher densities.

5·2. *Effects of strong magnetic field on K^* masses.* – Firstly, due to Lowest Landau Level (LLL) contribution, the different polarized states of charged vector (K^{*+}) meson are splitted in mass and charged kaon (K^+) masses will also be modified. Furthermore,

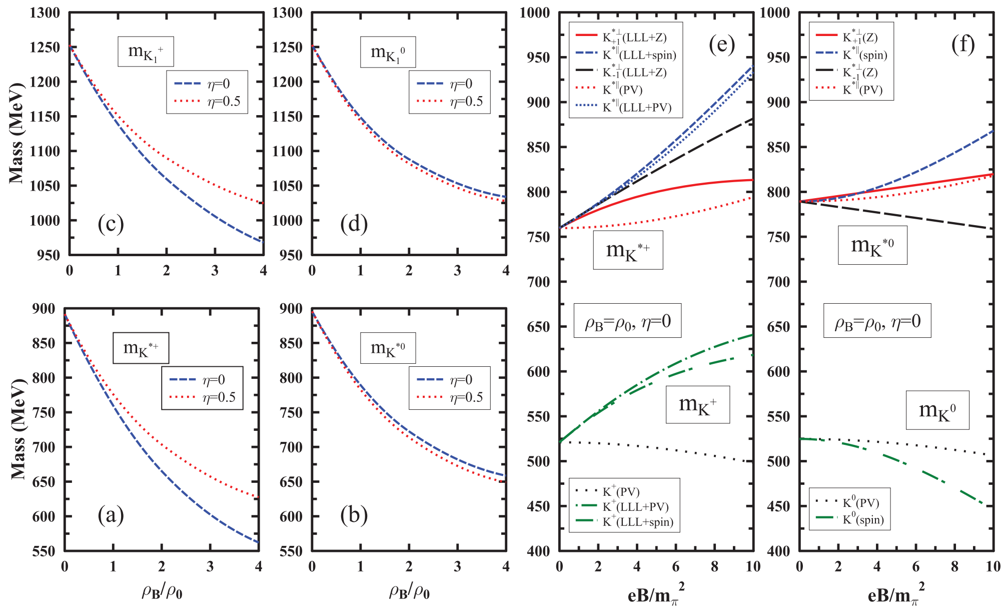

Fig. 1. – The masses of vector K^* and axial vector K_1 meson are plotted against ρ_B/ρ_0 at zero magnetic field in subplots (a)–(d). In subplots (e), (f), vector (K^*) and pseudoscalar (K) meson masses are plotted with eB/m_π^2 at baryon density $\rho_B = \rho_0$ in $\eta = 0$ nuclear matter. Here "LLL" represents the lowest Landau level contribution, "PV" represents the PV mixing considered through effective Lagrangian, "spin" represents the PV mixing considered through spin-magnetic field interaction, and "Z" represents the anomalous Zeeman splitting. The three polarization states of vector K^* meson $S_z = +1, 0$, and -1 are written as $K^{*\perp}_{+1}, K^{*||}, K^{*\perp}_{-1}$.

due to PV mixing incorporated through effective interaction term, there is a level repulsion between longitudinal part of vector ($K^{*||}$) and pseudoscalar (K) meson. The mass of vector (pseudoscalar) meson increases (decreases) with magnetic field. The effects of Landau quantization and PV mixing are shown in subplots (e) and (f) in fig. 1.

The PV mixing, incorporated through spin-magnetic field interaction, leads to decrease (increase) in the mass of pseudoscalar K (vector $K^{*||}$) meson. The masses of transverse polarized states are also modified, due to spin-magnetic field interaction, due to unequal quark masses and/or charges for the K^* meson. This is known as anomalous Zeeman splitting which is due to the non-vanishing intrinsic magnetic moment of the meson.

5·3. *Decay width of open strange mesons.* – In fig. 2, the partial decay widths of vector K^* meson are shown in subplots (a)–(d), after including the effects of Landau quantization and PV mixing (through the spin mixing ($-\mu_i \cdot B$) term) on the masses [12]. The contribution from each polarization state of vector meson is shown separately. The qualitative behavior of decay width, as a function of magnetic field, reflects the medium dependence of the masses of mesons involved in that decay channel.

In subplots (e)–(h), we have plotted the partial decay widths of K_1 meson in nuclear medium, as calculated within the $^3P_0$ model. The vacuum partial decay width for $K_1 \rightarrow K^*\pi$ is estimated within a phenomenological approach [12, 23]. The variation trends in the decay width are caused by the interplay between the mass modifications of the involved $K^*(K^{*+}$ or $K^{*0})$ and $K_1(K_1^+$ or $K_1^0)$ mesons. We have also computed the $K_1 \rightarrow K^*\pi$ decay width within a phenomenological Lagrangian approach in the isospin

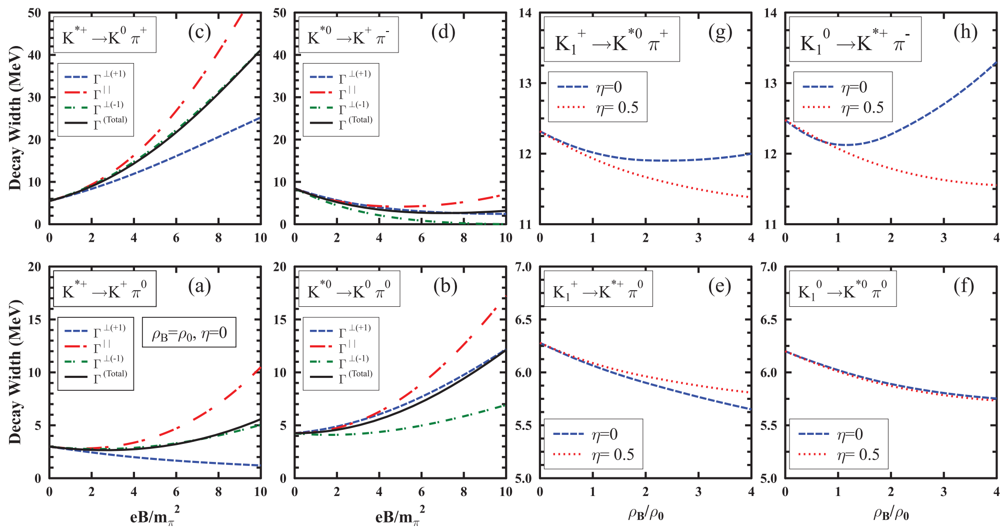

Fig. 2. – Decay widths of K^* meson plotted with eB/m_π^2 at $\rho_B = \rho_0$ with $\eta = 0$ in subplots (a)–(d). The effects of Landau quantization and PV mixing, considered through the $(-\mu_i \cdot B)$ term, are included. In subplots (e)–(h), decay width of axial vector K_1 meson, is plotted as a function of relative baryon density (ρ_B/ρ_0), as calculated within the $^3P_0$ model.

asymmetric nuclear matter [12]. The present study of open strange particles might find relevance in HIC experiments at the RHIC low-energy scan programme and the High Acceptance DiElectron Spectrometer (HADES) Collaboration at GSI, Darmstadt.

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