Heavy vector and axial-vector mesons in hot and dense asymmetric strange hadronic matter

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We calculate the effects of finite density and temperature of isospin asymmetric strange hadronic matter, for different strangeness fractions, on the in-medium properties of vector (D^*, D_s^*, B^*, B_s^*) and axial-vector (D_1, D_{1s}, B_1, B_{1s}) mesons, using the chiral hadronic SU(3) model and QCD sum rules. We focus on the evaluation of in-medium mass-shift and shift in decay constant of above vector and axial-vector mesons. In the quantum chromodynamics sum rule approach, the properties, e.g., the masses and decay constants of vector and axial-vector mesons are written in terms of quark and gluon condensates. These quark and gluon condensates are evaluated in the present work within the chiral SU(3) model, through the medium modification of scalar-isoscalar fields σ and ζ, the scalar-isovector field δ, and the scalar dilaton field χ, in the strange hadronic medium which includes both nucleons as well as hyperons. As we shall see in detail, the masses and decay constants of heavy vector and axial-vector mesons are affected significantly from isospin asymmetry and the strangeness fraction of the medium, and these modifications may influence the experimental observables produced in heavy-ion collision experiments. The results of present investigations of in-medium properties of vector and axial-vector mesons at finite density and temperature of strange hadronic medium may be helpful for understanding the experimental data from heavy-ion collision experiments in particular for the compressed baryonic matter (CBM) experiment of the FAIR facility at GSI, Germany.

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I. INTRODUCTION

The aim of relativistic heavy-ion collision experiments is to explore the different phases of the quantum chromodynamics (QCD) phase diagram so as to understand the underlying strong interaction physics of quantum chromodynamics. The different regions of the QCD phase diagram can be explored by varying the beam energy in the high energy heavy-ion collision experiments. The nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) experiments explore the region of the QCD phase diagram at low baryonic densities and high temperatures. However, the objective of the compressed baryonic matter (CBM) experiment of the FAIR project (at GSI, Germany) is to study the region of the phase diagram at high baryonic density and moderate temperature. In nature these kinds of phases may exist in astrophysical compact objects, e.g., in neutron stars. Among the many different observables which may be produced in the CBM experiment, one of them may be the production of mesons having charm quark or antiquark. Experimentally, charm meson spectroscopy as well as their in-medium properties are also of interest from the point of view of the PANDA experiment of the FAIR project, where $\bar{p}A$ collisions will be performed. The possibility of the production of open or hidden charm mesons motivates the theoretical physicist to study the properties of these mesons in dense nuclear matter. The discovery of many open or hidden charm or bottom mesons at CLEO, Belle or BABAR experiments [1–3] attract the attention of theoretical groups to study the properties of these mesons.

In the present paper, our objective is to work out the in-medium masses and decay constants of the heavy charmed vector (D^*, D_s^*) and axial vector (D_1, D_{1s}) as well as bottom vector (B^*, B_s^*) and axial-vector (B_1, B_{1s}) mesons in the isospin asymmetric strange hadronic medium, at finite density and temperature. The initial interest in the understanding of the properties of heavy flavor mesons was stimulated from the observation of the J/ψ suppression phenomenon [4–7]. In the high temperature regime, the J/ψ suppression can be explained either using the color screening or the statistical hadronization model [8–12]. However, for the moderate temperature and finite baryonic densities the effects of hadronic absorptions and comover interactions also come into the picture and cannot be neglected [13]. The evaluation of in-medium properties of open charm D mesons may also play an important role in understanding J/ψ suppression in heavy-ion collisions. The reason is, the higher charmonium states are considered as a major source of J/ψ mesons. However, if the D mesons undergo mass drop in the nuclear matter and the in-medium mass of $D\bar{D}$ pairs falls below the threshold value of excited charmonium states, then these charmonium states can also decay to $D\bar{D}$ pairs and may cause a decrease in the yield of J/ψ mesons. The in-medium properties of D and $\bar{D}$ mesons may also play an important role in revealing the possibility of formation of charmed mesic nuclei. The charmed mesic nuclei are the bound states of charm mesons and nucleon formed through strong interactions. In Ref. [14], the mean field potentials of D and $\bar{D}$ mesons were calculated using the quark meson coupling (QMC) model under local density approximation and the possibilities of the formation of bound states of D^-, D^0, and $\bar{D}^0$ mesons with Pb(208) were examined. The properties of charmed mesons in the nuclei had also been studied using the unitary meson-baryon coupled channel approach and incorporating the heavy-quark

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spin symmetry [15,16]. The theoretical investigations of open or hidden charmed meson properties at finite density and temperature of the nuclear matter may help us in understanding their production rates, decay constants, decay widths, etc., in heavy-ion collision experiments.

The in-medium properties of open charm and bottom mesons are evaluated using the quark meson coupling model in Refs. [14,17]. The medium modified masses of D mesons, calculated within the QMC model, were used as input for the study of mass modification of J/ψ mesons in the nuclear matter [18]. Borel transformed QCD sum rules, involving operator product expansion (OPE) up to dimension-4, were used to investigate the in-medium modifications of pseudoscalar D mesons and the impact of these modifications on charmonium suppression in Ref. [19]. The study of open charm mesons within QCD sum rules were further carried out in Ref. [20], where the even as well as odd part of OPE was used to study mass spitting between the pseudoscalar D-$\bar{D}$ doublet. In the study of mass shift of D mesons in Ref. [20], a positive mass shift of about +45 MeV was obtained at normal nuclear saturation density, whereas in the work of Ref. [19], a negative mass shift of magnitude 50 MeV was observed. The properties of pseudoscalar B mesons as well as charm strange D_s mesons were also studied in Ref. [20] and these studies were further extended to the scalar D mesons in Ref. [21]. In Ref. [22], the OPE for pseudoscalars D and B mesons was performed for both the normal-order operators and also for non-normal-ordered operators. A projection method to calculate the higher order contributions to OPE, for in-medium QCD sum rules of D mesons was used in Ref. [23]. A study on the decomposition of higher dimensional condensates into the vacuum part and a medium part was done recently in [24]. The heavy quark expansion for the study of D and B mesons in the nuclear matter was performed in [25]. The Wilson coefficients and four quark condensates in the QCD sum rules for the medium modification of D mesons were calculated in Ref. [26].

The properties of open and hidden charm mesons have also been studied to great extent in coupled channel approach [27–35]. Using the separable potential technique between meson-baryon interactions and SU(3) symmetry among the u, d, and c quarks, the spectral properties of D mesons were investigated in the nuclear matter at zero [27] and finite temperatures [28]. In the work of Refs. [29,30], the properties of D mesons were studied in the SU(4) sector including the strangeness channel also and breaking SU(4) symmetry through the exchange of vector mesons. In Ref. [31], the properties of D and $\bar{D}$ mesons were investigated self-consistently in the coupled channel approach including the Pauli blocking effects and mean field potential of baryons. The properties of scalar charm resonances and hidden charm resonances were also studied using the coupled channel method in [32]. The study of open charm mesons within the coupled channel approach was further improved by using heavy quark spin-flavor symmetry and the in-medium properties of charmed pseudoscalar and vector mesons as well as charm baryon resonances Λ_c, Σ_c, Ξ_c, and Ω_c were investigated [16,33]. In Ref. [34], the chiral unitary coupled channel approach was used to study the interactions of light vector mesons with baryon and nuclei and the possibilities of the formation of quasibound states of vector mesons with baryons were observed. These studies were also extended to the charm sector where hidden charm states were observed and which has consequences on J/ψ suppression [34]. The baryons states with charm degree of freedom can be generated dynamically within the coupled channel approach and also incorporating the heavy quark spin symmetry [35].

The chiral hadronic SU(3) model is generalized to the SU(4) and SU(5) sector, for investigating the in-medium properties of pseudoscalar D and B mesons [36–38]. The in-medium mass modifications of scalar, vector, and axial-vector heavy D and B mesons were investigated using the QCD sum rules in the nuclear matter in [39,40]. In Ref. [41], we studied the mass modifications of scalar, vector, and axial-vector heavy charmed and bottom mesons at finite density of the nuclear matter using the chiral SU(3) model and QCD sum rules. In this approach, we evaluated the medium modifications of quark and gluon condensates in the nuclear matter through the medium modification of scalar isoscalar fields σ and ζ and the scalar dilaton field χ. In the present paper, we shall evaluate the properties of vector and axial-vector mesons in the hot and dense isospin asymmetric strange hadronic medium. In the QCD sum rules, the properties of the above mesons are modified through the quark and gluon condensates. Within the chiral hadronic model the quark and gluon condensates are written in terms of scalar fields σ, ζ, and δ and the scalar dilaton field χ. We shall evaluate the σ, ζ, δ, and χ fields and hence the quark and gluon condensates in the medium consisting of nucleons and hyperons and shall find the mass shift and shift in decay constants of heavy vector and axial-vector mesons.

The study of the decay constant of heavy mesons plays an important role in understanding the strong decay of heavy mesons, their electromagnetic structure as well radiative decay width. The study of B meson decay constants is important for B_d-$\bar{B}_d$ and B_s-$\bar{B}_s$ mixing [42]. The decay constants of vector D^* and B^* mesons are helpful for calculations of strong coupling in $D^*D\pi$ and $B^*B\pi$ mesons using light cone sum rules [43]. Extensive literature is available on the calculations of decay constants of heavy mesons in the free space, for example, the QCD sum rules based on OPE of the two-point correlation function, heavy-quark expansion [44], sum rules in heavy-quark effective theory [45,46], and sum rules with gluon radiative corrections to the correlation functions up to two loops [47–49] or three loops [50]. However, the in-medium modifications of decay constants of heavy mesons had been studied in symmetric nuclear matter only [51,52]. The thermal modification (at zero baryonic density) of decay constants of heavy vector mesons was investigated in Ref. [53] and it was observed that the values of decay constants remained almost constant up to 100 MeV, but above this decrease sharply with increase in temperature.

We shall present this work as follows: In Sec. II, we shall briefly describe the chiral SU(3) model which is used to evaluate the quark and gluon condensates in the strange hadronic matter. Section III will introduce the QCD sum rules which we shall use in the present work along with the chiral model to evaluate the in-medium properties of mesons. In Sec. IV, we shall present our results of the present investigation and possible discussion on these results. Section V will summarize the present work.

II. CHIRAL SU(3) MODEL

The basic theory of strong interaction, the QCD, is not directly applicable in the nonperturbative regime. To overcome this limitation, the effective theories, constrained by the basic properties, e.g., chiral symmetry and scale invariance of QCD, are constructed. The chiral SU(3) model is one such effective model based on the nonlinear realization and broken scale invariance as well as spontaneous breaking properties of chiral symmetry [54,55]. The glueball field χ is introduced in the model to account for the broken scale invariance properties of QCD. The model had been used successfully in the literature to study the properties of hadrons at finite density and temperature of the nuclear and strange hadronic medium. The general Lagrangian density of the chiral SU(3) model involve the kinetic energy terms, the baryon meson interactions, self-interaction of vector mesons, scalar mesons-meson interactions, as well as the explicit chiral symmetry breaking term [54]. From the Lagrangian densities of the chiral SU(3) model, using the mean field approximation, we find the coupled equations of motion for the scalar fields σ, ζ, δ, and the scalar dilaton field χ [55]. These coupled equations of motion for the above fields are solved for the different values of isospin asymmetry parameter I, and strangeness fraction f_s, of the hadronic medium at finite density and temperature. The isospin asymmetry parameter I is defined by the relation, $I = \frac{\rho_n - \rho_p}{2\rho_B}$, where ρ_n and ρ_p are the number densities of neutrons and protons, respectively, and ρ_B is baryon density. The strangeness fraction of the medium is given by $f_s = \frac{\sum_i |s_i| \rho_i}{\rho_B}$. Here, s_i is the number of strange quarks and ρ_i is the number density of the i^{th} baryon [55].

In the present work, for the evaluation of vector and axial-vector meson properties using QCD sum rules, we shall need the light quark condensates $\langle \bar{u}u \rangle$ and $\langle \bar{d}d \rangle$, the strange quark condensate $\langle \bar{s}s \rangle$, and the scalar gluon condensate $\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \rangle$. In the chiral effective model, the explicit symmetry breaking term is introduced to eliminate the Goldstone bosons and can be used to extract the scalar quark condensates $\langle q\bar{q} \rangle$, in terms of scalar fields σ, ζ, δ, and χ. We write [55]

$$\sum_i m_i \bar{q}_i q_i = -\mathcal{L}_{\text{SB}} \tag{1}$$

$$= \left(\frac{\chi}{\chi_0}\right)^2 \left(\frac{1}{2} m_\pi^2 f_\pi (\sigma + \delta) + \frac{1}{2} m_\pi^2 f_\pi (\sigma - \delta) + \left(\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi\right) \zeta\right). \tag{2}$$

From Eq. (2), light scalar quark condensates $\langle \bar{u}u \rangle$ and $\langle \bar{d}d \rangle$, and the strange quark condensate $\langle \bar{s}s \rangle$, can be written as

$$\langle \bar{u}u \rangle = \frac{1}{m_u} \left(\frac{\chi}{\chi_0}\right)^2 \left[\frac{1}{2} m_\pi^2 f_\pi (\sigma + \delta)\right], \tag{3}$$

$$\langle \bar{d}d \rangle = \frac{1}{m_d} \left(\frac{\chi}{\chi_0}\right)^2 \left[\frac{1}{2} m_\pi^2 f_\pi (\sigma - \delta)\right], \tag{4}$$

and

$$\langle \bar{s}s \rangle = \frac{1}{m_s} \left(\frac{\chi}{\chi_0}\right)^2 \left[\left(\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi\right) \zeta\right], \tag{5}$$

respectively. Also, we know that because of the broken scale invariance property of QCD, the trace of energy momentum tensor is nonvanishing (trace anomaly) and is equal to the scalar gluon condensates. The trace anomaly property of QCD can be mimicked in the effective chiral model through the scale breaking Lagrangian density which can be further used to evaluate the trace of energy momentum tensor. Comparing, the trace of energy momentum tensor evaluated from the effective chiral model, to the trace of energy momentum tensor of basic QCD theory, we can express the gluon condensate in terms of scalar fields σ, ζ, δ, and χ [54,55]. This relation is given by

$$\left\langle \frac{\alpha_s}{\pi} G^a{}_{\mu\nu} G^{a\mu\nu} \right\rangle = \frac{8}{9} \left[(1-d)\chi^4 + \left(\frac{\chi}{\chi_0}\right)^2 \times \left(m_\pi^2 f_\pi \sigma + \left(\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi\right) \zeta\right)\right]. \tag{6}$$

Equations (3)–(6) give us the expressions for different scalar quark condensates and gluon condensate in terms of scalar fields within the chiral SU(3) model. It should be noted that, for massless quarks, the second term in Eq. (6), arising from explicit symmetry breaking will be absent and the scalar gluon condensate becomes proportional to the fourth power of the dilaton field χ, in the chiral SU(3) model.

III. QCD SUM RULES FOR VECTOR AND AXIAL-VECTOR HEAVY MESONS IN STRANGE HADRONIC MATTER

In this section, we shall discuss the QCD sum rules [39,40], to be used later along with the chiral SU(3) model, for the evaluation of in-medium properties of vector and axial-vector mesons in asymmetric strange hadronic matter. We know that the starting point in the QCD sum rules is to write the two-point correlation function, $\Pi_{\mu\nu}(q)$, which is the Fourier transform of the expectation value of the time-ordered product of isospin averaged currents $J_\mu(x)$ and can be decomposed into the vacuum part, a static nucleon part, and pion bath contribution [41,56,57]. For the vector and axial-vector mesons the average particle-antiparticle currents are given by, $J_\mu(x) = J^\dagger_\mu(x) = \frac{\bar{c}(x)\gamma_\mu q(x) + \bar{q}(x)\gamma_\mu c(x)}{2}$ and $J_{5\mu}(x) = J^\dagger_{5\mu}(x) = \frac{\bar{c}(x)\gamma_\mu \gamma_5 q(x) + \bar{q}(x)\gamma_\mu \gamma_5 c(x)}{2}$, respectively. Here, q denotes the u, d, or s quark (depending upon the type of meson under investigation), whereas c denotes the heavy charm quark (for B mesons the quark c will be replaced by the bottom b quark). We know that the charmed mesons D^+, D^-, D^0, and $\bar{D}^0$ have the quark compositions, $c\bar{d}$, $d\bar{c}$, $c\bar{u}$, and $u\bar{c}$, respectively. The mesons D^+ and D^- are particle antiparticles to each other and, similarly, D^0 and $\bar{D}^0$ mesons. The above listed charm mesons belong to the isospin $D(D^+, D^0)$ and $\bar{D}(D^-, \bar{D}^0)$ doublets. In the present work, we shall find the average mass shift for particle-antiparticle pairs, i.e., for, D^+ and D^-, and for D^0 and $\bar{D}^0$, under centroid approximation [19,40]. In this way, we will also be able to study the mass splitting of the isospin doublet from the isospin asymmetry of the medium. To find the mass splitting of particles and antiparticles in the nuclear medium one has to consider the even and odd part of QCD sum rules [20]. For example, in Ref. [20] the mass splitting between pseudoscalar D and $\bar{D}$ mesons was investigated using the even and odd QCD sum rules, whereas in [19,39,40] the mass shift of D mesons was investigated under centroid approximation. It means, in the present work, we assumed the degeneracy between particle-antiparticle mass. Note that the sum rules for D^0 can be obtained from the D^+ just by replacing the d quark with the u quark [22].

In the literature of QCD sum rules, the pion bath contributions are used to evaluate the effects of finite temperature of the medium on the properties of mesons [56,57]. In our present approach, however, the effects of finite temperature of the medium on the properties of vector and axial-vector mesons are evaluated through the temperature dependence of scalar fields σ, ζ, δ, and χ, which will appear through the static one nucleon part [36,41,54,55,58,59]. For the case of vector and axial-vector mesons, the correlation function $T^N_{\mu\nu}(\omega,\boldsymbol{q})$, which appears in the static nucleon part, can be written in terms of forward scattering amplitudes $T_N(\omega,\boldsymbol{q})$ (corresponding to vector and axial-vector mesons) and $T^0_N(\omega,\mathbf{q})$ (corresponding to scalar and pseudoscalar mesons), as follows [51,60]:

$$T^N_{\mu\nu}(\omega,\boldsymbol{q}) = T_N(\omega,\mathbf{q})\left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right) + T^0_N(\omega,\mathbf{q})\frac{q_\mu q_\nu}{q^2}. \quad (7)$$

Note that in the present work, we are interested in the properties of vector and axial-vector mesons and therefore, the second term of Eq. (7) will not contribute. The forward scattering amplitude $T_N(\omega,\mathbf{q})$, in the limit, $\mathbf{q}\to 0$, can be written in terms of spin averaged spectral density ρ, as follows [52,60]:

$$T_N(\omega,\mathbf{q}) = \int_{-\infty}^{+\infty} du \frac{\rho(u,\mathbf{q}=0)}{u-\omega-i\epsilon} = \int_0^\infty du^2 \frac{\rho(u,\mathbf{q}=0)}{u^2-\omega^2}. \quad (8)$$

Near the pole positions of vector and axial-vector mesons, the phenomenological spectral densities can be further related to the D^*N and D_1N scattering matrix $\mathcal{T}$, and can be parametrized with three unknown parameters a,b, and c as discussed in Refs. [19,39–41]. Also, the in-medium mass shift, $\delta m_{D^*/D_1}$, of vector and axial-vector mesons can be related to their scattering length a_{D^*/D_1}, through parameter a and is given by [19,39–41]

$$\begin{aligned}\delta m_{D^*/D_1} &= \sqrt{m^2_{D^*/D_1} + \left(\frac{\rho_B}{2m_N}\frac{a}{f^2_{D^*/D_1}m^2_{D^*/D_1}}\right)} - m_{D^*/D_1}\\ &= \sqrt{m^2_{D^*/D_1} + \left(-\frac{\rho_B}{2m_N}8\pi(m_N + m_{D^*/D_1})a_{D^*/D_1}\right)}\\ &\quad - m_{D^*/D_1}.\end{aligned} \quad (9)$$

The shift in the decay constant of vector or axial-vector mesons can be written as [51]

$$\delta f_{D^*/D_1} = \frac{1}{2f_{D^*/D_1}m^2_{D^*/D_1}}\left(\frac{\rho_B}{2m_N}b - 2f^2_{D^*/D_1}m_{D^*/D_1}\delta m_{D^*/D_1}\right). \quad (10)$$

From Eqs. (9) and (10) we observe that, to find the value of mass shift and shift in the decay constant of mesons, we first need to know the value of unknown parameters a and b. For achieving this, the equations for Borel transformation of the scattering matrix on the phenomenological side are equated to the Borel transformation of the scattering matrix for the OPE side [19,39,40]. The detailed expressions for the Borel transformed equations of heavy vector and axial-vector mesons can be found in Refs. [40,41]. The unknown parameters a and b, will appear in these Borel transformed equations. To obtain the values of these two unknown parameters, the Borel transformed equation of the meson under study is differentiated with respect to $\frac{1}{M^2}$, so that we could have two equations and two unknowns. By solving those two coupled equations we will be able to get the values of parameters a and b.

Also note that the Borel transformed equations of vector and axial-vector mesons will depend on the nucleon expectation values of quark condensates $\langle\bar{q}q\rangle$, $\langle q^\dagger iD_0q\rangle$, $\langle\bar{q}g_s\sigma Gq\rangle$, and $\langle\bar{q}iD_0iD_0q\rangle$, and the gluon condensate $\langle\frac{\alpha_s}{\pi}G^a{}_{\mu\nu}G^{a\mu\nu}\rangle$ [41]. The nucleon expectation values of the operators can be expressed in terms of the expectation value of operators at finite baryonic density and vacuum expectation value [41,56,57,60]. As discussed earlier, in Sec. II, the scalar quark condensate $\langle\bar{q}q\rangle$ and the gluon condensates $\langle\frac{\alpha_s}{\pi}G^a{}_{\mu\nu}G^{a\mu\nu}\rangle$ can be evaluated within the chiral SU(3) model. The condensates, $\langle\bar{q}g_s\sigma Gq\rangle$ and $\langle\bar{q}iD_0iD_0q\rangle$, can be approximated in terms of scalar quark condensates $\langle\bar{q}q\rangle_{\rho_B}$ [61]. The value of $\langle\bar{q}q\rangle$, evaluated within the chiral SU(3) model, can be used in the equations of $\langle\bar{q}g_s\sigma Gq\rangle$ and $\langle\bar{q}iD_0iD_0q\rangle$, for an improved evaluation of these condensates within the chiral model. The value of the quark condensate, $\langle q^\dagger iD_0q\rangle$, for the light quark is equal to 0.18 GeV$^2\rho_B$ and for the strange quark it is 0.018 GeV$^2\rho_B$ [61].

Note that the bottom mesons, i.e., B^+, B^-, B^0, and $\bar{B}^0$, have the quark compositions, $u\bar{b}$, $b\bar{u}$, $d\bar{b}$, and $b\bar{u}$, respectively. Comparing the quark compositions of charm and bottom mesons, e.g., for B^+ and $\bar{D}^0$, we observe that both have the same light u quark and differ in heavy flavor antiquark. In the QSR equations of D mesons, the quark condensates corresponding to only the light quark appear along with the masses of heavy quark and mesons. It means the QSR equation of B^+ will differ from that of $\bar{D}^0$ merely by masses of heavy flavor mesons (both have the same light quark). The same correspondence exists for B^- and D^0, B^0 and D^-, and $\bar{B}^0$ and D^+. Thus sum rules for the bottom B mesons can be obtained from the sum rules of D mesons by replacing, m_c with m_b, D^* (D_1) with B^* (B_1), and also by replacing Λ_c (Σ_c) with Λ_b (Σ_b). The same strategy was applied to obtain the OPE for pseudoscalar B mesons from D mesons in Refs. [22,39,40,51,52]. When we move from nonstrange to strange mesons, the light quark is replaced by the strange quark. Therefore, the QCD sum rules for the strange vector mesons are obtained by using the strange condensates in place of light quark condensates. Hilger in Ref. [20] used the same strategy for obtaining the sum rules for pseudoscalar D_s mesons from D meson sum rules. Now the sum rule equations of D_s mesons will also differ from B_s mesons by the mass of heavy flavor mesons only and therefore, sum rules for strange

B_s mesons are obtained by replacing masses of D_s mesons by corresponding masses of B_s mesons.

IV. RESULTS AND DISCUSSIONS

In this section, we shall discuss the results of present investigation of in-medium mass shift and shift in decay constant of vector $[D^*(D^{*+},D^{*0},D_s^*)$ and $B^*(B^{*+},B^{*0},B_s^*)]$ and axial-vector $[D_1(D_1^+,D_1^0,D_{1s})$ and $B_1(B_1^+,B_1^0,B_{1s})]$ mesons in isospin asymmetric strange hadronic matter. First we list the values of various parameters used in the present work on vector and axial-vector mesons. Nuclear matter saturation density adopted in the present investigation is 0.15 fm^{-3}. The coupling constants of heavy baryons with nucleons and heavy charmed or bottom mesons appear in the hadronic matrix elements of the heavy baryon transitions to nucleon. These coupling constants are calculated using the light cone QCD sum rules [62]. The average value of coupling constants $g_{D^*N\Lambda_c}$ and $g_{D^*N\Sigma_c}$ is 3.86 [40,51,62]. As we shall discuss later, the shift in masses and decay constants of vector and axial-vector mesons are not much sensitive to the values of coupling constants and, therefore, we used the same values for all vector and axial-vector mesons under investigation [40,51], i.e., we use $g_{D^*N\Lambda_c} \approx g_{D^*N\Sigma_c} \approx g_{D_1N\Lambda_c} \approx g_{D_1N\Sigma_c} \approx g_{B^*N\Lambda_b} \approx g_{B^*N\Sigma_b} \approx g_{B_1N\Lambda_b} \approx g_{B_1N\Sigma_b}$ equal to 3.86 [40]. The masses of quarks, namely, up (u), down (d), strange (s), charm (c), and bottom (b), used in the present work are 0.005, 0.007, 0.095, 1.35, and 4.7 GeV, respectively.

In Table I, we mentioned the values of masses m, decay constants f, and threshold parameters s_0 of vector and axial-vector mesons [40,51]. The values of decay constants of strange vector mesons are calculated in terms of decay constants of nonstrange vector mesons in Refs. [50,63–65]. In Ref. [50], using QCD sum rules, the values for $f_{D_s^*}$ and $f_{B_s^*}$ are found to be $1.21 f_{D^*}$ and $1.20 f_{B^*}$, respectively. In [63], the decay constants of $f_{D_s^*}$ are calculated from the simulations of twisted mass QCD and are observed to be $1.16 f_{D^*}$. The values of $f_{B_s^*}$ in [65] are observed to be $1.16 f_{B^*}$. In our present calculations, for strange vector and axial-vector mesons, we used the value 1.16 times the decay constant of the respective nonstrange meson, i.e., the values of $f_{D_s^*}$, $f_{B_s^*}$, $f_{D_{1s}}$, and $f_{B_{1s}}$ are $1.16 f_{D^*}$, $1.16 f_{B^*}$, $1.16 f_{D_1}$, and $1.16 f_{B_1}$, respectively [63,65]. The continuum threshold parameter s_0 defines the scale below which the continuum contribution vanishes [57]. The values of continuum threshold parameters s_0 are chosen so as to reproduce the experimental observed vacuum values of the masses of vector and axial-vector mesons [40,51]. We assume that the various coupling constants and continuum threshold parameters are not subjected to medium modifications.

TABLE I. We tabulate the values of masses m, decay constants f, and threshold parameters s_0 of vector and axial-vector mesons.

	D^{*+}	D^{*0}	B^{*0}	B^{*+}	D_s^*	B_s^*
m (GeV)	2.01	2.006	5.325	5.323	2.112	5.415
f (GeV)	0.270	0.270	0.195	0.195	$1.16 f_{D^*}$	$1.16 f_{B^*}$
s_0 (GeV^2)	6.5	6.5	35	35	7.5	38
	D_1^+	D_1^0	B_1^0	B_1^+	D_{1s}	B_{1s}
m (GeV)	2.423	2.421	5.723	5.721	2.459	5.828
f (GeV)	0.305	0.305	0.255	0.255	$1.16 f_{D_1}$	$1.16 f_{B_1}$
s_0 (GeV^2)	8.5	8.5	39	39	9.5	41

TABLE II. We tabulate the Borel windows, i.e., range of squared Borel mass parameter M^2, within which shift in mass δm and decay constant δf remain stable. The values shown in the table are in GeV^2 units and are given for both vector and axial-vector mesons.

	D^{*+}	D^{*0}	D_s^*	B^{*+}	B^{*0}	B_s^*
δm	(4.5–6.5)	(4.5–6.5)	(5.0–7.0)	(30–33)	(30–33)	(31–34)
δf	(3.3–4.9)	(3.3–4.9)	(3.8–5.3)	(26–31)	(26–31)	(27–31)
	D_1^+	D_1^0	D_{1s}	B_1^+	B_1^0	B_{1s}
δm	(5.4–9.4)	(5.4–9.4)	(5.9–9.9)	(33–38)	(33–38)	(36–40)
δf	(4.2–7.2)	(4.2–7.2)	(5.0–8.0)	(30–34)	(30–34)	(32–36)

To describe the exact mass (decay) shift of the above mesons we have chosen a suitable Borel window, i.e., the range of the squared Borel mass parameter M^2, within which there is almost no variation in the mass and decay constant. In Table II, we mentioned the Borel windows, as observed in the present calculations for the mass shift and shift in the decay constant of vector and axial-vector mesons. In our calculations, we observe that masses and decay constants of vector and axial-vector mesons are stable in different regions of M^2 and therefore, different Borel windows for masses and decay constants of respective mesons are mentioned in Table II. This is consistent with the observations of Ref. [51]. Our further discussion in the present section is divided into three subsections. In Sec. IV A, we shall discuss the behavior of scalar fields and condensates in the strange hadronic medium, at zero and finite temperatures. Sections IV B and IVC will be devoted to presenting the results on vector and axial-vector mesons, respectively.

A. Scalar fields and condensates

We start with the discussion on the behavior of quark and gluon condensates for different strangeness fractions and isospin asymmetry parameters of the strange hadronic medium. In literature, the quark condensates are evaluated to leading order in nuclear density using the Feynman-Hellmann theorem and model-independent results were obtained in terms of the pion nucleon sigma term [66,67]. Using the Feynman-Hellmann theorem, the quark condensate at finite density of nuclear matter is expressed as a sum of vacuum value and a term dependent on energy density of nuclear matter. In the model-independent calculations, the interactions between nucleons were neglected and free space nucleon mass was used. If one uses only the leading order calculations for the evaluation of quark condensates above nuclear matter density, then the quark condensates decrease very sharply and almost vanish around $3\rho_0$. In Ref. [68], the Dirac-Brueckner approach with the Bonn boson-exchange potential was used to include the higher order corrections and to find the quark condensates in the nuclear matter above the nuclear matter density. The calculations show that at higher density the quark condensates decrease more slowly as compared to leading order predictions.

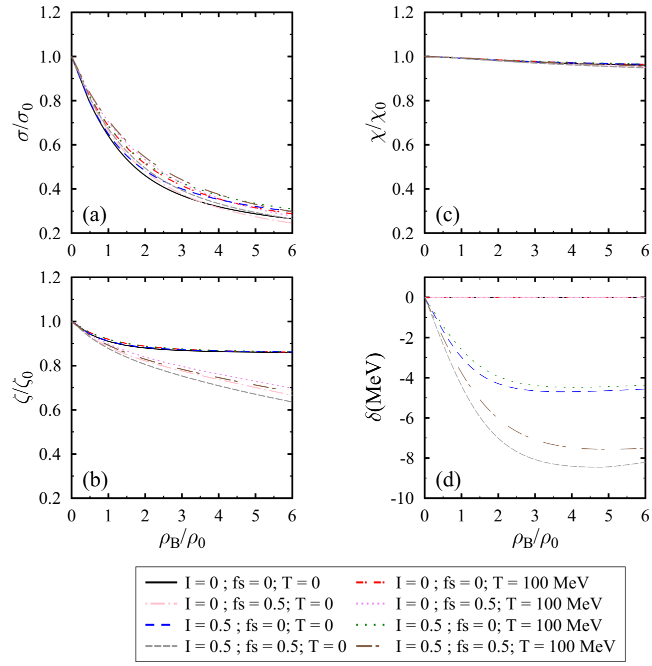

FIG. 1. (Color online) In the above figure, (a)–(c) show the variation of ratio of the in-medium value to the vacuum value of scalar fields, σ/σ_0, ζ/ζ_0, and χ/χ_0 as a function of baryonic density, ρ_B (in units of nuclear saturation density, ρ_0). In (d) we have shown the scalar-isovector field δ as a function of density of medium. We show the results at temperatures $T = 0$ and 100 MeV. For each value of temperature, the results are plotted for isospin asymmetry parameters $I = 0$ and 0.5, and the strangeness fractions f_s =0 and 0.5.

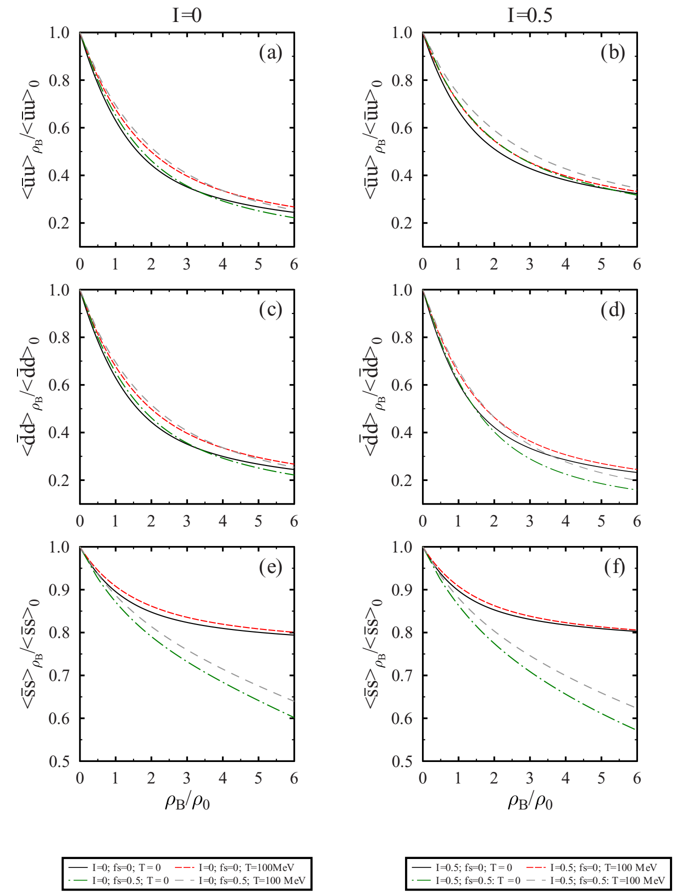

FIG. 2. (Color online) In the above figure, we plot the ratio of in-medium quark condensate to vacuum condensate, as a function of baryonic density ρ_B (in units of nuclear saturation density, ρ_0). We compare the results at isospin asymmetric parameters $I = 0$ and 0.5. For each value of isospin asymmetry parameter I, the results are shown for strangeness fractions f_s =0 and 0.5 and temperatures $T = 0$ and 100 MeV.

As discussed earlier, in the chiral SU(3) model, used in the present work, the quark and gluon condensates are expressed in terms of scalar fields σ, ζ, δ, and χ [55,58]. In Fig. 1, we show the variation of ratio of in-medium value to vacuum value of scalar fields, as a function of baryonic density of strange hadronic medium. We show the results for temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature T, the results are plotted for isospin asymmetry parameters $I = 0$ and 0.5 and the strangeness fractions $f_s = 0$ and 0.5. From Fig. 1, we can see that the scalar fields σ and ζ vary considerably as a function of baryonic density of medium, whereas the scalar field χ has little density dependence. For example, in the symmetric nuclear medium ($I = 0$ and $f_s = 0$), at density $\rho_B = \rho_0$ ($4\rho_0$), the values of scalar fields σ, ζ, and χ, are observed to be 0.64 σ_0 (0.31 σ_0), 0.91 ζ_0 (0.86 ζ_0), and 0.99 χ_0 (0.97 χ_0). The symbols, σ_0, ζ_0, and χ_0 denote the vacuum values of scalar fields and have values -93.29, -106.75, and 409.76 MeV, respectively. It is observed that, at high baryon density, the strange scalar-isoscalar field ζ, varies considerably as a function of strangeness fraction f_s, as compared to nonstrange scalar isoscalar field σ. For example, in the symmetric medium ($I = 0$), at baryon density $4\rho_0$, as we move from $f_s = 0$ to $f_s = 0.5$, the value of ζ changes by 14%, whereas the value of σ changes by 1% only. However, the effect of isospin asymmetry of the medium is more on the values of the σ field as compared to the ζ field. For example, in the nuclear medium ($f_s = 0$), at baryon density $\rho_B = 4\rho_0$, as we move from $I = 0$ to 0.5, the values of the nonstrange scalar field σ and the strange scalar field ζ changes by 10.25% and 0.24%, respectively. However, in the strange medium, at $f_s = 0.5$, the percentage change in the values of σ and ζ is 7.2% and 7%, respectively. Because the scalar meson σ has light quark content (u and d quarks) and the ζ meson has strange quark content (s quark) and therefore, the former is more sensitive to the isospin asymmetry of the medium (property of u and d quarks) and the latter is to the strangeness fraction. For the finite baryonic density of the medium, the scalar fields undergo less drop at nonzero temperature of the medium, as compared to the zero temperature situation. This effect of temperature is more pronounced at finite strangeness and higher baryonic density of the medium. For example, in symmetric nuclear matter, at baryonic density $\rho_B = \rho_0$, for a change of temperature from $T = 0$ to $T = 100$ MeV, the magnitude of scalar field σ, is increased by approximately 6%. However, at $\rho_B = 4\rho_0$ and $f_s = 0.5$, the increase in the magnitude of σ is 12%. The observed behavior of scalar fields with the temperature of the medium, in the present chiral SU(3)

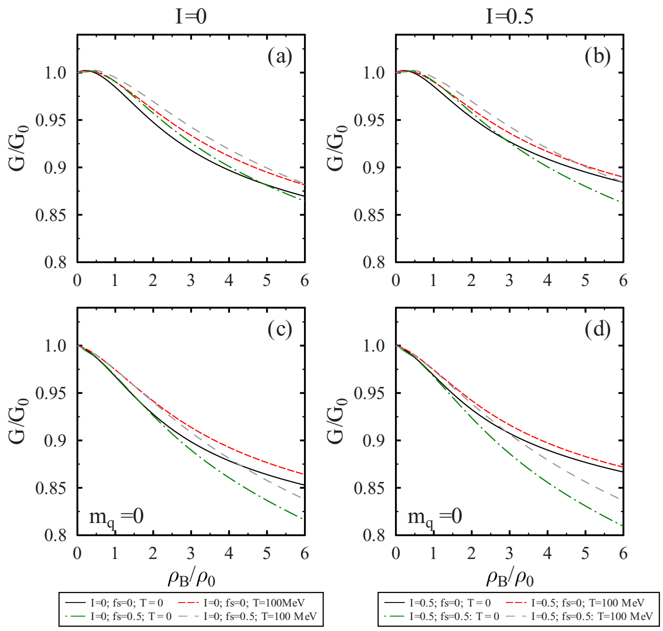

FIG. 3. (Color online) In the above figure, we plot the ratio of in-medium scalar gluon condensate to the vacuum value of gluon condensate, as a function of baryonic density ρ_B (in units of nuclear saturation density ρ_0). We compare the results at isospin asymmetric parameters $I = 0$ and 0.5. For each value of isospin asymmetry parameter I, the results are shown for strangeness fractions $f_s = 0$ and 0.5 and temperatures $T = 0$ and 100 MeV. In the y axis, $G = \langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \rangle$ and G_0 denotes the expectation value of gluon condensate for zero density and temperature.

hadronic model, is consistent with the calculation within the chiral quark mean field model discussed in Ref. [69].

In Figs. 2 and 3, the ratios of the in-medium value to the vacuum value of scalar quark and gluon condensates, respectively, are plotted as a function of baryonic density of the hadronic medium. We show the results for light quark condensates $\langle \bar{u}u \rangle$, $\langle \bar{d}d \rangle$, the strange quark condensate $\langle \bar{s}s \rangle$, and the gluon condensates $\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \rangle$. In Table III, we tabulate the values of the ratio of these condensates for quantitative understanding. In this table, $\langle \bar{u}u \rangle_0$, $\langle \bar{d}d \rangle_0$, and $\langle \bar{s}s \rangle_0$, denotes the vacuum values of quark condensates and in the chiral SU(3) model these are -1.401×10^{-2} GeV^3, -1.401×10^{-2} GeV^3, and -4.671×10^{-2} GeV^3, respectively. We observe that, for a given value of temperature T, isospin asymmetry parameter I, and the strangeness fraction f_s, as a function of baryonic density, the magnitude of the values of the quark condensate decreases with respect to vacuum value. This is because the values of quark condensates are proportional to the scalar fields σ and ζ [see Eqs. (3)–(5)]. As discussed above, the magnitude of these scalar fields undergo drop as a function of density of baryonic matter and this further causes a decrease in the magnitude of quark condensates. As we move from the symmetric to the asymmetric medium, due opposite contribution of scalar-isovector mesons δ, the value of condensate $\langle \bar{u}u \rangle$ increases, whereas that of $\langle \bar{d}d \rangle$ decreases.

In isospin symmetric medium ($I = 0$), below baryon density $\rho_B = 3.3\rho_0$, as we move from the nonstrange medium, i.e., $f_s = 0$, to the strange medium with $f_s = 0.5$, the magnitude of light quark condensates $\langle \bar{u}u \rangle$ increases. Above baryon density, $\rho_B = 3.3\ \rho_0$, the magnitude of the values of light quark condensates is more in the nonstrange medium ($f_s = 0$) as compared to the strange medium with finite f_s. From Fig. 2, we observe that, as a function of density of baryonic matter, we always observe a decrease in the values of quark condensates. This supports the expectation of chiral symmetry restoration at high baryonic density. However, in the linear Walecka model [70,71] and also in the Dirac-Brueckner approach [68], the values of quark condensates are observed to increase at higher values of baryonic density and cause hindrance to chiral symmetry restoration. The possible reason for this may be that the chiral invariance property was not considered in these calculations [68]. As the strange quark condensate $\langle \bar{s}s \rangle$ is proportional to the strange scalar-isoscalar field ζ, the behavior of this field as a function of various parameters of the medium is also reflected in the values of the strange quark condensate $\langle \bar{s}s \rangle$. For fixed baryon density ρ_B and isospin asymmetry parameter I, as we move from the nonstrange to the strange hadronic medium, the values of strange condensate decrease.

TABLE III. We tabulate the ratio of the in-medium value to the vacuum value of scalar quark and gluon condensates.

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\frac{\langle u\bar{u}\rangle}{\langle u\bar{u}\rangle_0}$	0	0.62	0.29	0.67	0.33	0.66	0.38	0.70	0.39
	0.5	0.65	0.29	0.69	0.33	0.70	0.39	0.74	0.42
$\frac{\langle d\bar{d}\rangle}{\langle d\bar{d}\rangle_0}$	0	0.63	0.29	0.67	0.35	0.60	0.28	0.65	0.30
	0.5	0.65	0.29	0.69	0.33	0.61	0.22	0.66	0.27
$\frac{\langle s\bar{s}\rangle}{\langle s\bar{s}\rangle_0}$	0	0.99	0.80	0.90	0.81	0.89	0.81	0.90	0.82
	0.5	0.87	0.68	0.88	0.71	0.86	0.65	0.88	0.69
$\frac{G}{G_0}$	0	0.98	0.89	0.99	0.91	0.98	0.90	0.99	0.91
	0.5	0.99	0.90	0.99	0.91	0.99	0.90	0.99	0.92
$\frac{G}{G_0}$ ($m_q = 0$)	0	0.96	0.87	0.97	0.89	0.96	0.88	0.97	0.89
	0.5	0.96	0.86	0.97	0.88	0.96	0.85	0.97	0.87

In Figs. 3(a) and 3(b), we consider the contribution of the finite quark mass term in the calculation of gluon condensates, whereas Figs. 3(c) and 3(d) are without the effect of the quark mass term. We observe that, as a function of baryonic density of the hadronic medium, the values of gluon condensates decrease. As one can see from Figs. 3(c) and 3(d), the effect of strangeness fractions are more visible at higher baryon densities. The calculations show that the gluon condensates have small density dependence as compared to quark condensates. This observation is consistent with earlier model independent calculations by Cohen [67] and also with the QMC model calculation in Ref. [72].

Also it is observed that, at zero baryonic density, the behavior of scalar fields and hence the scalar quarks and gluon condensates, as a function of temperature of the medium is opposite the situation of finite baryonic density. At $\rho_B = 0$, the drop in the scalar fields and scalar condensates increase (magnitude decreases) with the increase in temperature of the

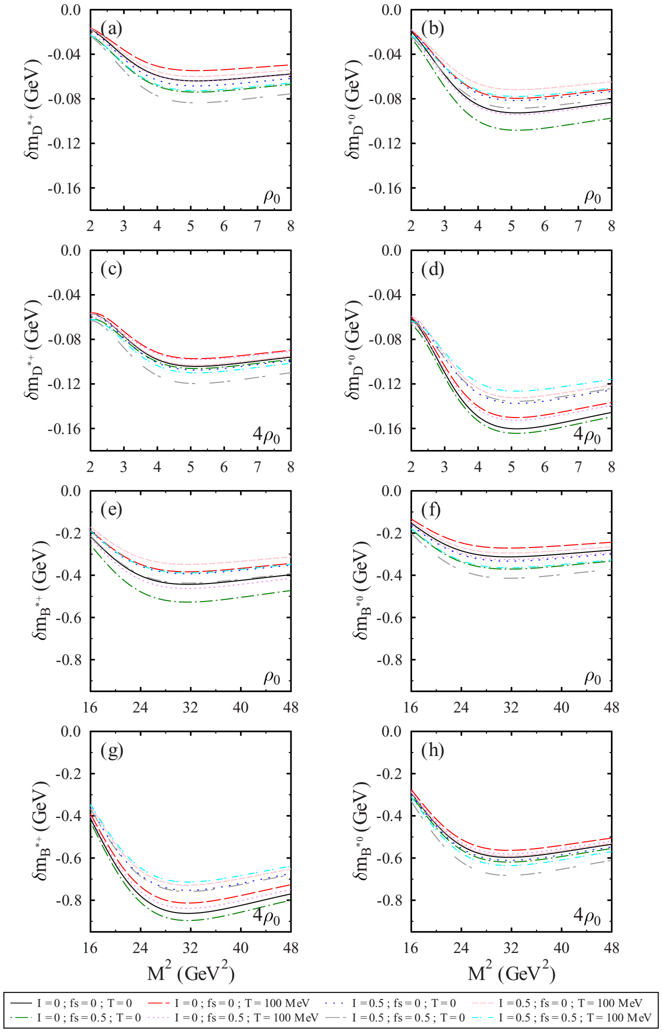

FIG. 4. (Color online) In the above figure, the variation of mass shift of vector mesons D^* (D^{*+} and D^{*0}) and B^* (B^{*+} and B^{*0}) is shown as a function of the squared Borel mass parameter M^2. We compare the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetric parameters $I = 0$ and 0.5 and the strangeness fractions $f_s = 0$ and 0.5.

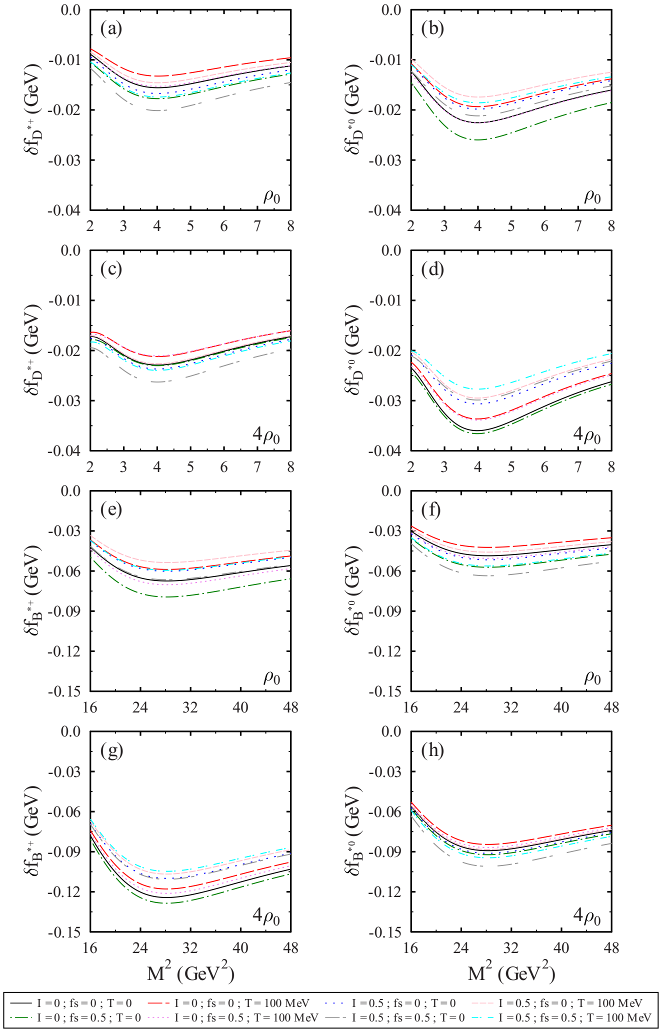

FIG. 5. (Color online) In the above figure, the variation of shift in the decay constant of vector mesons D^* (D^{*+} and D^{*0}) and B^* (B^{*+} and B^{*0}), is shown as a function of squared Borel mass parameter M^2. We compare the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetric parameters $I = 0$ and 0.5, and the strangeness fractions $f_s = 0$ and 0.5.

medium. Recall from the previous discussion, at finite ρ_B, the drop in the scalar fields and hence scalar condensates was decreasing (magnitude increasing) with increase in the temperature of the medium (see Figs. 2 and 3). However, for zero baryonic density, the change in the magnitude of scalar fields with the temperature is very small in the hadronic medium. For example, at $\rho_B = 0$, the magnitude of the scalar field σ (ζ) decreases by 0.06% (0.02%) as one move from $T = 0$ to $T = 100$ MeV. For a change of temperature from $T = 100$ to $T = 150$ MeV, the magnitude of σ (ζ) decreases by 2.5% (0.8%). The values of light quark condensate, strange quark condensate, and the gluon condensate with the zero quark mass term, at $\rho_B = 0$, changes by 2.75%, 0.85%, and 0.08%, respectively, as T is changed from 0 to 150 MeV. However, at very high temperature, possibly above critical temperature, the values of scalar condensates may change sharply [73]. As we discussed earlier, in literature the values of scalar condensates at finite temperatures and zero baryonic densities are calculated using the pion bath contributions [57]. Our observations on the behavior of condensates as a function of temperature, for zero baryonic density, are in accordance with the earlier findings [74–76].

B. Heavy vector mesons (D^*, B^*, D_s^*, and B_s^*)

In Fig. 4 (Fig. 5), we show the variation of mass shift (shift in decay constant) of vector mesons D^* and B^*, as a function of squared Borel mass parameter M^2. In each subplot, we compare the results for temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are plotted for isospin asymmetry parameters $I = 0$ ($f_s = 0$ and 0.5) and $I = 0.5$ ($f_s = 0$ and 0.5). We present the results at baryonic

TABLE IV. We tabulate the values of mass shift (in units of MeV) of heavy vector mesons D^* (D^{*+} and D^{*0}) and B^* (B^{*+} and B^{*0}).

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta m_{D^{*+}}$	0	−64	−104	−54	−97	−68	−104	−60	−97
	0.5	−74	−106	−64	−98	−83	−119	−72	−110
$\delta m_{D^{*0}}$	0	−92	−160	−79	−150	−81	−132	−71	−132
	0.5	−108	−164	−94	−152	−88	−135	−77	−126
$\delta m_{B^{*+}}$	0	−443	−862	−383	−813	−392	−752	−348	−728
	0.5	−527	−896	−462	−838	−437	−758	−388	−713
$\delta m_{B^{*0}}$	0	−312	−596	−271	−563	−333	−610	−294	−590
	0.5	−370	−618	−326	−580	−414	−682	−364	−635

densities ρ_0 and $4\rho_0$. In Table IV (Table V), we have written the values of shift in mass (decay constant) of these vector mesons. The difference in the masses of D^{*+} (B^{*+}) and D^{*0} (B^{*0}) mesons in the symmetric nuclear medium is from the different masses of u and d quarks, considered in the present investigation. Also we observe that, for a given value of the baryonic density and strangeness fraction, both the masses and decay constants of D^{*+} and B^{*0} (D^{*0} and B^{*+}) mesons, undergo more (less) drop in the asymmetric medium as compared to the symmetric medium. Note that the D^{*+} and B^{*0} mesons contain the light d quark, whereas the D^{*0} and B^{*+} mesons have the light u quark. As discussed earlier, the behavior of $\langle\bar{d}d\rangle$ and $\langle\bar{u}u\rangle$ condensates is opposite as a function of asymmetry of the medium and this causes the observed behavior of D^{*+} (B^{*0}) and D^{*0} (B^{*+}) mesons, as a function of asymmetry of the medium. As compared to the nuclear medium ($f_s = 0$), the drop in the masses and decay constant of D^* and B^* mesons is more in the strange hadronic medium (finite f_s). Also, the drop in the masses of D^* and B^* mesons increases with an increase in the baryonic density of the medium. At a given finite baryonic density, the nonzero temperature of the medium causes less drop in the

TABLE V. We tabulate the values of shift in the decay constant (in units of MeV) of heavy vector mesons D^* (D^{*+} and D^{*0}) and B^* (B^{*+} and B^{*0}).

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta f_{D^{*+}}$	0	−15	−23	−13	−21	−16	−23	−14	−22
	0.5	−17	−23	−15	−21	−20	−26	−17	−23
$\delta f_{D^{*0}}$	0	−22	−36	−19	−33	−19	−30	−17	−29
	0.5	−25	−36	−22	−33	−21	−29	−18	−27
$\delta f_{B^{*+}}$	0	−67	−124	−58	−117	−60	−109	−53	−106
	0.5	−79	−128	−70	−121	−66	−110	−59	−104
$\delta f_{B^{*0}}$	0	−48	−89	−42	−84	−51	−91	−45	−88
	0.5	−57	−92	−50	−86	−63	−100	−56	−94

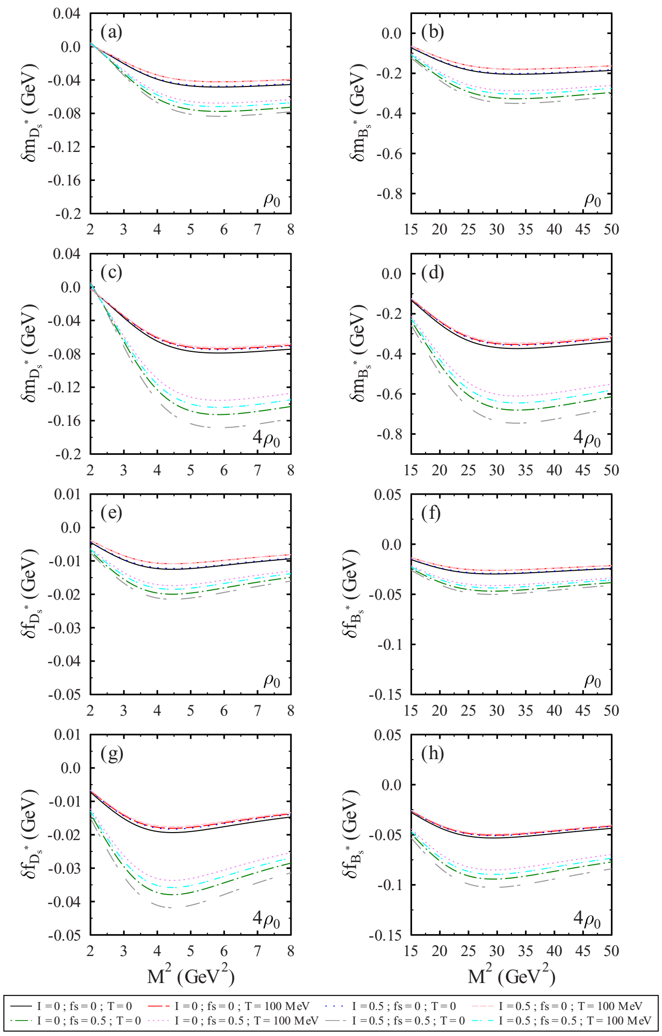

FIG. 6. (Color online) In the above figure, the variation of shift in mass and the decay constant of strange vector mesons D_s^* and B_s^* is shown as a function of squared Borel mass parameter M^2. We show the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetry parameter $I = 0$ and 0.5, and the strangeness fractions $f_s = 0$ and 0.5.

masses as well as the decay constant of D^* and B^* mesons, as compared to the zero temperature situation. This is because of the increase in the values of scalar fields and condensates as a function of temperature of the medium, at given finite baryonic density [69].

In Fig. 6 and Table VI, we present the variations of mass shift and shift in decay constant of D_s^* and B_s^* mesons. The charmed strange and bottom strange mesons have one strange quark s and one heavy quark. As discussed earlier, the in-medium properties of these mesons are calculated through the presence of strange quark condensate $\langle\bar{s}s\rangle$, in the OPE side of QCD sum rule equations [40]. The negative values of the shift in masses and decay constants show that these parameters of the strange charmed and bottom vector mesons undergo a drop in the hadronic medium. We notice that the effect of increasing either the density or strangeness fraction of the medium is to

TABLE VI. We tabulate the values of shift in masses and decay constants (in units of MeV) of heavy strange vector mesons D_s^* and B_s^*.

		I=0				I=0.5			
	f_s	T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta m_{D_s^*}$	0	−48	−79	−42	−74	−47	−74	−42	−72
	0.5	−77	−152	−67	−135	−83	−168	−71	−144
$\delta m_{B_s^*}$	0	−204	−373	−179	−353	−200	−357	−174	−345
	0.5	−326	−680	−287	−610	−350	−745	−304	−645
$\delta f_{D_s^*}$	0	−12	−19	−10	−18	−12	−18	−10	−17
	0.5	−19	−37	−17	−33	−21	−41	−18	−35
$\delta f_{B_s^*}$	0	−29	−53	−26	−50	−29	−51	−26	−49
	0.5	−46	−94	−41	−85	−50	−102	−43	−89

decrease the masses and decay constants of D_s^* and B_s^* mesons. However, as observed for D^* and B^* mesons, the masses and decay constants of D_s^* and B_s^* also increase with increase in temperature of the medium.

It may be noted that, among the various condensates present in the QCD sum rule equations, the scalar quark condensates $\langle \bar{q}q \rangle$ have the largest contribution for the medium modification of D and B meson properties. For example, if all the condensates are set to zero, except $\langle \bar{q}q \rangle$, then the shift in mass (decay constant) for the D^{*+} meson in the symmetric nuclear medium ($f_s = 0$ and $I = 0$) is observed to be $-69(-17.8)$ MeV for $\rho_B = \rho_0$ and can be compared to the values -64 (-15) MeV evaluated in the presence of all condensates. Also, the condensate $\langle q^\dagger i D_0 q \rangle$ is not evaluated within the chiral SU(3) model. In literature, the condensate $\langle q^\dagger i D_0 q \rangle$ is available in terms of the linear density formula only and hence the same is used in our calculations. Dependence of in-medium properties of D mesons on this condensate is negligible, at least up to the linear density approximation, as was also found in the literature [19,39,40,51]. However, at high density it might become important. Neglecting $\langle q^\dagger i D_0 q \rangle$ only, the values of mass shift (decay shift) in the symmetric medium at $\rho_B = \rho_0$, $2\rho_0$ and $4\rho_0$ are observed to be $-62(-15.5)$, $-89(-21)$, and $-97(-21)$ MeV, respectively. These values can be compared with the values $-64(-15)$, $-92(-22)$, and $-104(-23)$ MeV, respectively, which are computed in the situation when we considered the contribution of $\langle q^\dagger i D_0 q \rangle$ within linear density approximation. Thus, the mass shift (decay shift) for $D^{\star +}$ mesons at density $2\rho_0$ is changed by 3.58%(2.3%), whereas, at $4\rho_0$, the percentage change is 6.7%(4.8%).

The observed modifications of masses and the decay constant of vector mesons are not much sensitive to the values of the coupling constant of heavy baryons with nucleons and charmed and bottom mesons. For example, in symmetric nuclear matter, at nuclear saturation density ρ_0, for an increase (decrease) of 20% in the value of the coupling constant, the shift in the mass of D^{*+} mesons decreases (increases) by 1.4% (2.8%) only. As we discussed earlier, the continuum threshold parameters are chosen so as to reproduce the experimental observed vacuum values of the masses of charmed and bottom mesons mesons. The values of the threshold parameter affect significantly the masses and decay constants of D and B mesons. For example, for a decrease (increase) of 10% in the values of threshold parameter s_0, in symmetric nuclear matter, at $\rho_B = \rho_0$, an increase (decrease) of 29% (15%) is observed in the value of the mass shift of D^{*+} mesons.

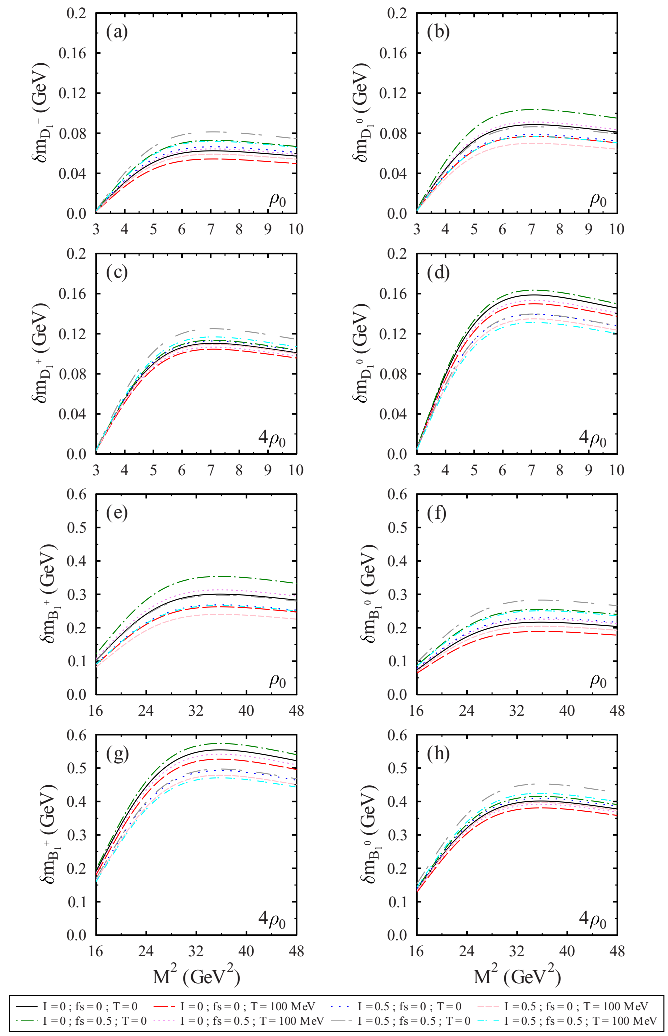

FIG. 7. (Color online) In the above figure, the variation of mass shift of axial-vector mesons, D_1 (D_1^+ and D_1^0) and B_1 (B_1^+ and B_1^0), is shown as a function of squared Borel mass parameter M^2. We compare the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetric parameters $I = 0$ and 0.5 and the strangeness fractions $f_s = 0$ and 0.5.

C. Heavy axial-vector mesons (D_1, B_1, D_{1s}, and B_{1s})

Figures 7 and 8 show the variation of the mass shift and shift in decay constants, respectively, of axial-vector mesons [D_1 (D_1^0 and D_1^+) and B_1 (B_1^0 and B_1^+)], as a function of the squared Borel mass parameter, i.e., M^2. In Tables VII and VIII, we

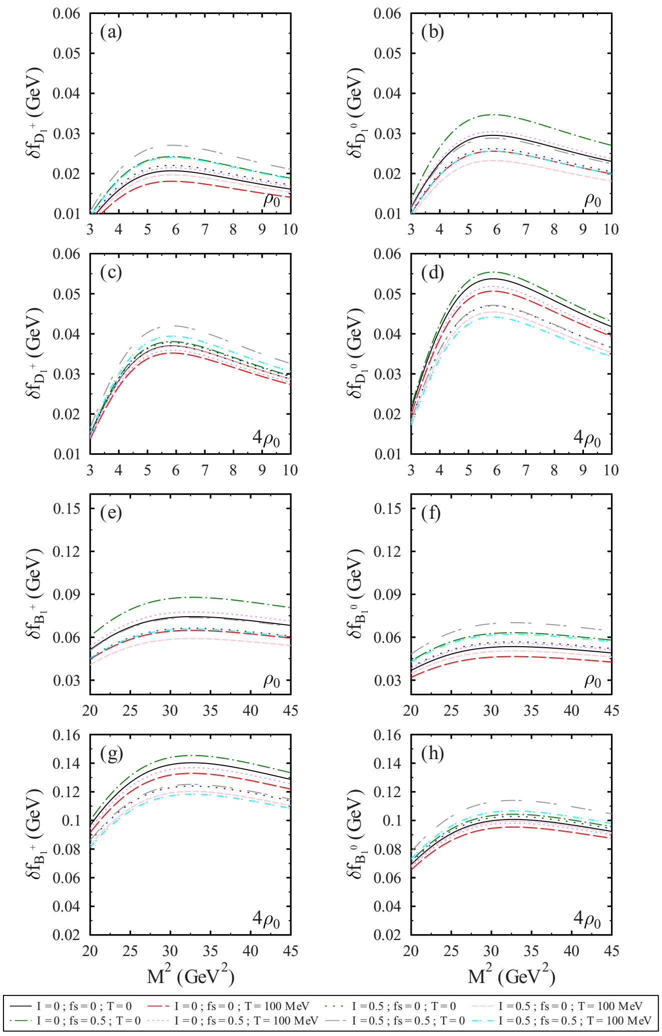

FIG. 8. (Color online) In the above figure, the variation of shift in decay constant of axial-vector mesons, D_1 (D_1^+ and D_1^0) and B_1 (B_1^+ and B_1^0), is shown as a function of squared Borel mass parameter M^2. We compare the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetric parameters $I = 0$ and 0.5 and the strangeness fractions $f_s = 0$ and 0.5.

tabulate the values of shift in mass and decay constants of these axial-vector mesons. Similarly, Fig. 9 and Table IX are for the strange axial-vector D_{1s} and B_{1s} mesons. For a constant value of strangeness fraction f_s, and isospin asymmetric parameter I, as a function of baryonic density, a positive shift in masses and decay constants of axial-vector mesons was observed. For a given density and isospin asymmetry, the finite strangeness fraction of the medium also causes an increase in the masses and decay constants of the above axial-vector mesons. For the axial-vector D_1 and B_1 meson doublet, as a function of isospin asymmetry of the medium, the values of the mass shift and decay shift of the D_1^0 (B_1^0) meson decreases (increases), whereas that of D_1^+ (B_1^+) increases (decreases). As discussed earlier, in the case of vector mesons, the reason for the opposite behavior of D and B mesons as a function of isospin asymmetry of the medium is the presence of light u quark in D_1^0 and B_1^+ mesons, whereas the mesons D_1^+ and B_1^0 have light d quark. At finite baryonic density, for the nuclear as well as the strange hadronic medium, the effect of finite temperature is to cause an increase in the values of positive mass shift of the axial-vector mesons with respect to the zero temperature case.

The mass shift and shift in decay constants of charmed and bottom vector and axial-vector mesons have been investigated in the past using QCD sum rules in symmetric nuclear matter only [40,51]. The values of the mass shift for D^* and B^* mesons, in leading order (next to leading order) calculations, were -70 (-102) and -340 (-687) MeV, respectively. For the axial-vector D_1 and B_1 mesons, the above values of mass shift changes to 66 (97) and 260 (522) MeV, respectively. The values of shift in decay constant for D^* and B^* mesons, in leading order (next to leading order), are found to be $-18(-26)$ and $-55(-111)$ MeV, whereas for D_1 and B_1 mesons these values change to 21(31) and 67 (134) MeV, respectively. We can compare the above values of mass shift (decay shift) to our results -63 (-20), -312 (-48.9), 62 (20), and 216 (53) MeV

TABLE VII. We tabulate the values of mass shift (in units of MeV) of heavy axial-vector mesons D_1 (D_1^+ and D_1^0) and B_1 (B_1^+ and B_1^0).

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta m_{D_1^+}$	0	62	110	54	104	66	112	59	109
	0.5	72	113	64	106	81	124	72	116
$\delta m_{D_1^0}$	0	88	158	168	149	78	140	69	134
	0.5	103	163	91	153	86	140	76	131
$\delta m_{B_1^+}$	0	300	554	262	526	268	492	240	478
	0.5	353	573	313	541	297	497	266	470
$\delta m_{B_1^0}$	0	216	401	189	380	229	409	204	396
	0.5	255	415	225	391	282	452	250	424

TABLE VIII. We tabulate the values of shift in decay constant (in units of MeV) of heavy axial-vector mesons D_1 (D_1^+ and D_1^0) and B_1 (B_1^+ and B_1^0).

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta f_{D_1^+}$	0	20	36	18	35	22	37	19	36
	0.5	24	38	21	36	27	41	24	39
$\delta f_{D_1^0}$	0	29	53	25	50	26	46	23	45
	0.5	34	55	30	51	28	47	25	44
$\delta f_{B_1^+}$	0	74	140	64	132	66	124	59	120
	0.5	87	145	77	136	73	125	65	118
$\delta f_{B_1^0}$	0	53	100	46	95	56	102	50	99
	0.5	63	104	55	98	70	113	62	106

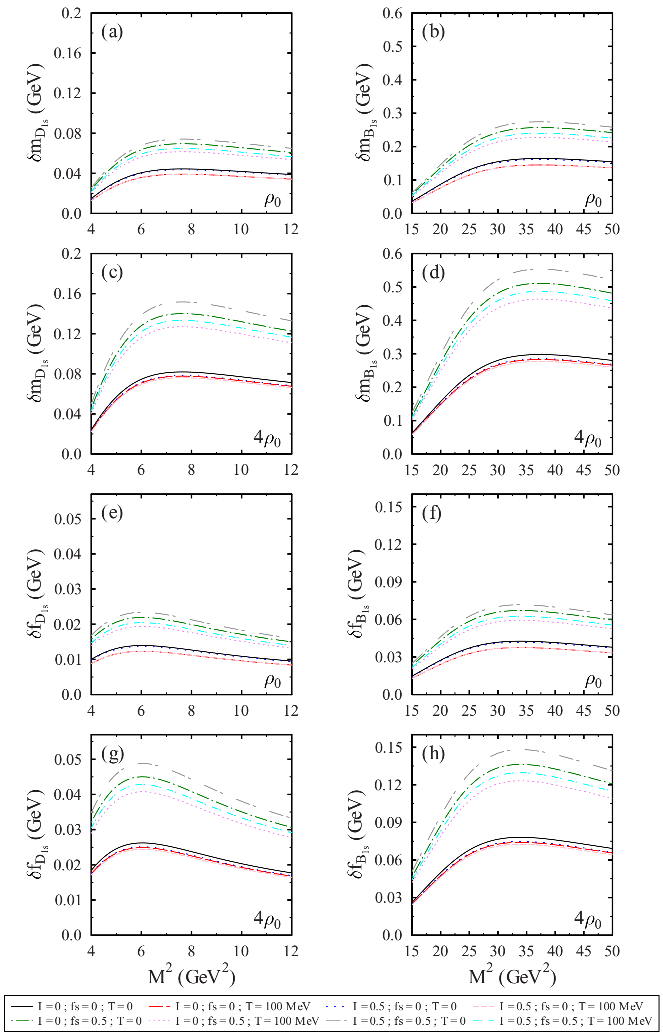

FIG. 9. (Color online) In the above figure, the variation of shift in mass and decay constant of strange axial-vector mesons D_{1s} and B_{1s}, is shown as a function of squared Borel mass parameter M^2. We show the results at temperatures $T = 0$ and $T = 100$ MeV. For each value of temperature, the results are shown for isospin asymmetry parameter $I = 0$ and 0.5, and the strangeness fractions $f_s = 0$ and 0.5.

for D^*, B^*, D_1, and B_1 mesons, evaluated using $m_u = m_d = 7$ MeV, in symmetric nuclear matter ($I = 0$ and $f_s = 0$). As discussed earlier, in our calculations, for strange mesons, we used the value of decay constant equal to 1.16 times the decay constant of nonstrange mesons. However, as an example, if we use, $f_{D_s} = 1.19 f_D$, then the values of mass shift, at ρ_0 ($I = 0$, $f_s = 0$), for vector and axial-vector mesons, are observed to be -46 and 44 MeV, respectively, and can be compared with the values -48 and 42 MeV, respectively, obtained using $f_{D_s} = 1.16 f_D$.

In [20,21], it was observed that beyond linear density approximation there occurs strong splitting between the particle-antiparticle mass. In these work, the correlation function was parametrized, using the Lehmann representation, into the form, $\mathrm{Im}\,\pi(\omega,0) = \Delta\pi(\omega) = \pi F_+\delta(\omega - m_+) - \pi F_-\delta(\omega + m_-)$, such that, $m_\pm = m \pm \Delta m$ and $F_\pm = F \pm \Delta F$. Here, m is mass center and Δm is the mass splitting between particle antiparticles. This correlation function was further used in the odd and even part of QCD sum rules. However, in our present approach, following the work of [19,40], the correlation function is divided into the vacuum part and a medium-dependent part and the average mass shift was obtained. In Ref. [77], the mass splitting between vector and axial-vector mesons had been studied using the Weinberg sum rules.

TABLE IX. We tabulate the values of shift in masses and decay constants (in units of MeV) of heavy strange axial-vector mesons D_{1s} and B_{1s}.

	f_s	I=0				I=0.5			
		T=0		T=100		T=0		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta m_{D_{1s}}$	0	44	81	39	77	43	78	39	76
	0.5	69	140	61	127	74	151	64	133
$\delta m_{B_{1s}}$	0	164	297	145	282	161	285	145	276
	0.5	257	510	227	463	274	553	239	486
$\delta f_{D_{1s}}$	0	14	26	12	24	13	25	12	24
	0.5	21	45	19	40	23	48	20	42
$\delta f_{B_{1s}}$	0	42	78	37	74	41	74	37	72
	0.5	67	136	59	123	71	148	62	129

In the self-consistent coupled channel approach of Ref. [16], the repulsive optical potential for D^* mesons had been reported which is complementary to our calculations within QCD sum rules. The observed negative values of mass shift for D^* and B^* mesons in nuclear and strange hadronic matter, in our calculations, favor the decay of higher charmonium and bottomonium states to $D^*\bar{D}^*$ and $B^*\bar{B}^*$ pairs and hence may cause the quarkonium suppression. However, the axial-vector mesons undergo a positive mass shift in the nuclear and strange hadronic medium and hence the possibility of decay of excited charmonium and bottomonium states to $D_1\bar{D}_1$ and $B_1\bar{B}_1$ pairs is suppressed. The observed effects of isospin asymmetry of the medium on the mass modifications of D and B mesons can be verified experimentally through the ratios $\frac{D^{*+}}{D^{*0}}$, $\frac{B^{*+}}{B^{*0}}$, $\frac{D_1^+}{D_1^0}$ and $\frac{B_1^+}{B_1^0}$, whereas the effects of strangeness of the matter can be seen through the ratios $\frac{D^*}{D_S^*}$, $\frac{B^*}{B_S^*}$, $\frac{D_1}{D_{1S}}$, and $\frac{B_1}{B_{1S}}$. The traces of observed medium modifications of masses and decay constants can be seen experimentally in the strong decay width and leptonic decay width of heavy mesons [52]. For example, in Ref. [43] the couplings $g_{D^*D\pi}$ and $g_{B^*B\pi}$ were studied using the QCD sum rules and strong decay width of charged vector D^{*+} mesons for the strong decay; $D^{*+} \longrightarrow D^0\pi^+$ were evaluated using the formula,

$$\Gamma(D^* \longrightarrow D\pi) = \frac{g^2_{D^*D\pi}}{24\pi m^2_{D^*}}|k_\pi|^3, \tag{11}$$

where, pion momentum k_π is

$$k_\pi = \sqrt{\frac{\left(m^2_{D^*} - m^2_D + m^2_\pi\right)^2}{(2m_{D^*})^2} - m^2_\pi}. \tag{12}$$

In Eq. (11), coupling $g^2_{D^*D\pi} = 12.5 \pm 1$, and m_{D^*} and m_D denote the masses of vector and pseudoscalar meson, respectively. From Eq. (11), we observe that the values of decay width depend upon the masses of vector and pseudoscalar mesons, i.e., D^* and D, respectively. Using vacuum values for the masses of D mesons, the values of decay width $\Gamma(D^{*+} \longrightarrow D^0\pi^+)$ are observed to be 32 ± 5 keV [43]. However, as we discussed in our present work, the charmed mesons get modified in the hadronic medium and this must lead to the medium modification of decay width of these mesons. For example, if we consider the in-medium masses of vector mesons from our present work and for pseudoscalar mesons we use the in-medium masses from Ref. [36] [in this reference the mass modifications of pseudoscalar D mesons were calculated using the chiral SU(4) model in the nuclear and strange hadronic medium], then in the nuclear medium ($f_s = 0$), at baryon density $\rho_B = \rho_0$, the values of decay width $\Gamma(D^{*+} \longrightarrow D^0\pi^+)$ are observed to be 219 keV and 31 keV at asymmetry parameter $I = 0$ and 0.5, respectively. In the strange medium ($f_s = 0.5$), the above values of decay width will change to 84 and 25 keV at $I = 0$ and 0.5, respectively. We observe that the decay width of heavy mesons vary appreciably because of medium modification of heavy meson masses. In our future work we shall evaluate in detail the effects of medium modifications of masses and decay constants of heavy charmed and bottom mesons on the above-mentioned experimental observables.

V. SUMMARY

In short, we computed the mass shift and shift in decay constants of vector and axial-vector charm and bottom mesons, in asymmetric hadronic matter, consisting of nucleon and hyperons, using the phenomenological chiral model and QCD sum rules, at zero as well as at finite temperature. For this, first the quark and gluon condensates were calculated using the chiral hadronic model and then, using these values of condensates as input in QCD sum rules, the in-medium properties of vector and axial-vector mesons were evaluated. We observed a negative (positive) shift in the masses and decay constants of vector (axial-vector) mesons. The magnitude of shift increases with an increase in the density of baryonic density of matter. The properties of mesons are seen to be sensitive for the isospin asymmetry as well as the strangeness fraction of the medium. The isospin asymmetry of the medium causes the mass splitting between isospin doublets. The presence of hyperons in addition to nucleons cause more decrease (increase) in the masses and decay constant of vector (axial-vector) mesons. The finite temperature of the medium (at finite baryonic density) is observed to cause an increase in the masses and decay constants of heavy mesons. The observed effects on the masses and decay constants of heavy vector and axial-vector mesons may be reflected experimentally in the production ratio of open charm mesons as well as in their decay width. The negative mass shift of charmed vector mesons as observed in the present calculations may cause the formation of bound states with the nuclei as well as the decay of excited charmonium states to $D^*\bar{D}^*$ pairs causing charmonium suppression. The present work on the in-medium meson properties may be helpful in understanding the experimental observables of CBM and PANDA experiments of the FAIR project at GSI Germany.

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