Masses and decay widths of scalar D_0 and D_{s0} mesons in a strange hadronic medium

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Masses and decay constants of scalar D_0 and D_{s0} mesons in isospin asymmetric strange hadronic matter at finite temperature are evaluated using QCD sum rules and a chiral SU(3) model. In-medium light quark condensates, $\langle \bar{u}u\rangle_{\rho_B}$ and $\langle \bar{d}d\rangle_{\rho_B}$; strange quark condensates, $\langle \bar{s}s\rangle_{\rho_B}$; and gluon condensates, $\langle \frac{\alpha_s}{\pi} G^a{}_{\mu\nu} G^{a\mu\nu}\rangle_{\rho_B}$, needed in QCD sum rule calculations are evaluated using a chiral SU(3) model. As an application, we calculate the in-medium partial decay width of scalar D_0 (D_{s0}) mesons decaying to $D + \pi$ ($D_s + \pi$) pseudoscalar mesons using a $^3P_0$ model. The medium effects in their decay widths are assimilated through the modification in the masses of these mesons. These results may be helpful to understand the possible outcomes of future experiments like the Compressed Baryonic Matter and anti-Proton Annihilation at Darmstadt experiments at the GSI Facility for Antiproton and Ion Research where the study of charmed hadrons is a major goal.

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I. INTRODUCTION

In-medium study of D mesons is an area of intense interest [1–13] because it may have possible consequences on the yield of open charm mesons [14–16] and hidden charm mesons [17–19]. Here, the behavior of in-medium masses and the spectral width of D mesons may play an important role in the theoretical observation of their yield and hence in the final yield of the charmonium. It was proposed by Matsui and Satz [20] that the decrease in the yield of the J/ψ state in heavy-ion collisions due to the color screening effect should be considered as a probe of the production of the quark gluon plasma (QGP) that existed in the early universe. Since then, imperative results in favor of J/ψ suppression have been observed in experiments at the CERN Super Proton Synchrotron and the BNL Relativistic Heavy Ion Collider (RHIC) [21–24]. Further, statistical recombination of primordially produced charm quark pairs may also significantly affect the yield of J/ψ mesons [25–27].

If the drop in the mass of D mesons in medium is large enough, then the higher charmonium states may decay to $D\bar{D}$ pairs instead of the J/ψ state and this will further support the suppression of J/ψ in heavy-ion collision (HIC) experiments. On the contrary, if the mass of D mesons increases in the medium, as was observed in Polyakov-loop-extended Nambu Jona-Lasinio model calculations, then these mesons may act as facilitators to the production of the J/ψ state in HIC experiments [28]. In-medium masses and decay constants of D mesons can be used in the conventional QCD sum rules to investigate in-medium D mesons' couplings with $DD^*\pi$ pions [29]. Further, these in-medium couplings may be used in the meson exchange model to find the J/ψ absorption cross sections by light π and ρ mesons [29,30].

Moreover, the study of D mesons in nuclear as well as in strange hadronic matter might shed light on the formation of the bound state of D mesons with nucleons [5] as well as with hyperons [6]. Here, by the term "strange hadronic medium" we mean that in addition to nucleons the effect of hyperons is also considered to investigate in-medium properties of D_0 and D_{s0} mesons. Also it is expected that, in the heavy-ion collision experiments strange matter may be produced [31–36]; therefore, the study of the in-medium properties of open charmed mesons at finite values of strangeness fraction becomes important. Further, the calculation of in-medium ratios of decay constants, $f_{D_{s0}}/f_{D_0}$, of charmed scalar mesons may also be used to measure the extent of flavor symmetry breaking in the strange hadronic matter as is done for pseudoscalar D mesons, f_{D_s}/f_D [37–39]. An upcoming experiment of the Facility for Antiproton and Ion Research (FAIR) project at GSI, Germany, will provide a unique opportunity to study the in-medium effects on the open and hidden charmed mesons. The Compressed Baryonic Matter (CBM) and anti-Proton Annihilation at Darmstadt (PANDA) experiments focus on the charmed spectroscopy and on the in-medium decay widths of the charmed hadrons. The CBM experiment may explore the phase of high baryonic density and moderate temperature, which will complement the work at the RHIC and the LHC. Apart from this, open charmed mesons are expected to be produced at the J-PARC facility, which motivates us to study the properties of D mesons in nuclear as well as strange hadronic matter [40]. The study of in-medium behavior of D mesons may help us to understand the experimentally observed elliptic flow, v_2, and the nuclear modification factor, R_{AA}, of these mesons [41,42].

On the phenomenological side, many methodologies have been developed to study the in-medium properties of D

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mesons. For example, the quark-meson coupling model (QMC) has predicted a negative shift in the mass of D mesons [5]. The self-consistent coupled-channel approach predicted a positive and a negative shift in the mass for pseudoscalar D mesons [9] and D_s mesons [10], respectively. This model was also used to investigate the scalar charm resonances of $D_{s0}(2317)$ and $D_0(2400)$ mesons [3] and revealed the large medium effects for the $D_{s0}(2317)$ meson as compared to the $D_0(2400)$ meson. Here the QMC model treats the quarks and gluons as degrees of freedom, and interactions between D mesons and nucleons are taken through the exchange of scalar and vector mesons. On the other hand, the self-consistent coupled-channel approach considers the hadrons as degrees of freedom [8], and this undergo necessary modifications, e.g., from SU(3) flavor [8] to SU(4) and breaking of SU(4) symmetry via the exchange of vector mesons [6,43].

Another approach uses QCD sum rules, in which the operator product expansion (OPE) is applied on the current-current correlation function [44]. In this analysis, using the Borel transformation the mass-dependent terms are related with the quark and gluon condensates [1,2]. The properties of the scalar D_0 mesons in nuclear medium have also been studied using QCD sum rule analysis up to the leading-order term [45] and the next-to-leading-order term [13]. In this technique, the quark and gluon condensates needed for the QCD sum rule analysis were calculated using the linear-density approximation. The chiral SU(3) model generalized to the SU(4) sector has also been used to investigate the shift in the masses of D mesons [4,12,46,47]. In Ref. [7], the chiral SU(3) model in conjunction with QCD sum rules was applied to study the in-medium masses of scalar mesons in nuclear medium. The in-medium properties of pseudoscalar, vector, and axial vector D mesons were investigated in Refs. [48,49]. In the present work, we evaluate the shift in the masses and decay constants of scalar D_0 and D_{s0} mesons in an asymmetric strange hadronic medium at finite temperatures. The in-medium properties of scalar D_{s0} mesons were not addressed in Ref. [7], and owing to the presence of strange quark, the behavior of these mesons in strange matter is of considerable interest.

Furthermore, as an application of our work we investigate the in-medium partial decay widths of D_0 and D_{s0} for the process $D_0 \to D + \pi$ ($D_{s0} \to D_s + \pi$). To achieve this goal, we use the $^3P_0$ model [50], which has been widely used in the past to evaluate the two-body decay of the various mesons [50–62]. The medium effects will be introduced through the medium-modified mass of these mesons. Here, we use the in-medium mass of pseudoscalar D mesons as calculated in our previous work using the chiral SU(3) model and the QCD sum rule approach [49]. Additionally we take the in-medium pion mass as calculated using the in-medium chiral perturbative theory [63]

This article is organized as follows. In Sec. II, we briefly describe the chiral SU(3) model to calculate in-medium quark and gluon condensates. The QCD sum rules used to investigate the in-medium masses and decay constants of D_0 and D_{s0} mesons are discussed in Sec. III, while the $^3P_0$ model used to evaluate the in-medium partial decay width of D_0 (D_{s0}) mesons is narrated in Sec. IV. In Sec. V, we present the various results of the present work, and finally in Sec. VI, we summarize the present work.

II. CHIRAL SU(3) MODEL

We use the chiral SU(3) model to calculate the in-medium values of light quark condensates ($\langle\bar{u}u\rangle_{\rho_B}$, $\langle\bar{d}d\rangle_{\rho_B}$), strange quark condensates ($\langle\bar{s}s\rangle_{\rho_B}$), and gluon condensates ($\langle\frac{\alpha_s}{\pi}G^a{}_{\mu\nu}G^{a\mu\nu}\rangle_{\rho_B}$). The chiral SU(3) model contains an effective Lagrangian density which includes a kinetic energy term, a baryon-meson interaction term which produces baryon mass, a self-interaction of vector mesons term which generates the dynamical mass of vector mesons, a scalar meson interaction term which induces the spontaneous breaking of chiral symmetry, and an explicit breaking term of chiral symmetry. In the strange hadronic medium, in-medium baryon masses are modified in the chiral SU(3) model through the exchange of scalar isoscalar mesons σ and ζ and the scalar isovector field δ. Within the mean-field approximation, from the effective Lagrangian density of the model, using the Euler-Lagrange equation $\frac{\partial\mathcal{L}}{\partial\phi} - \partial_\mu(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}) = 0$, where ϕ is the scalar field, we obtain equations of motion for σ, ζ, δ, and the scalar dilaton field χ. These are given as [64,65]

$$k_0\chi^2\sigma - 4k_1(\sigma^2+\zeta^2+\delta^2)\sigma - 2k_2(\sigma^3+3\sigma\delta^2) - 2k_3\chi\sigma\zeta - \frac{d}{3}\chi^4\left(\frac{2\sigma}{\sigma^2-\delta^2}\right) + \left(\frac{\chi}{\chi_0}\right)^2 m_\pi^2 f_\pi - \sum g_{\sigma i}\rho_i^s = 0, \tag{1}$$

$$k_0\chi^2\zeta - 4k_1(\sigma^2+\zeta^2+\delta^2)\zeta - 4k_2\zeta^3 - k_3\chi(\sigma^2-\delta^2) - \frac{d}{3}\frac{\chi^4}{\zeta} + \left(\frac{\chi}{\chi_0}\right)^2\left(\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right) - \sum g_{\zeta i}\rho_i^s = 0, \tag{2}$$

$$k_0\chi^2\delta - 4k_1(\sigma^2+\zeta^2+\delta^2)\delta - 2k_2(\delta^3+3\sigma^2\delta) + k_3\chi\delta\zeta + \frac{2}{3}d\chi^4\left(\frac{\delta}{\sigma^2-\delta^2}\right) - \sum g_{\delta i}\rho_i^s = 0, \tag{3}$$

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

respectively. In the above, the vacuum values of m_π (f_π) and m_K (f_K) are 139 (93.3) and 498 (122) MeV, respectively. Further the values of the parameters k_0, k_1, k_2, k_3, and k_4 are 2.54, 1.35, −4.78, −2.77, and −0.22, respectively, and these are fitted so as to reproduce the vacuum masses of η and η' mesons [66]. Further, ρ_i^s represents the scalar density for the ith baryon ($i = p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}$) and is defined as

$$\rho_i^s = \gamma_i \int \frac{d^3k}{(2\pi)^3} \frac{m_i^*}{E_i^*(k)} \times \left(\frac{1}{e^{(E_i^*(k)-\mu_i^*)/T} + 1} + \frac{1}{e^{(E_i^*(k)+\mu_i^*)/T} + 1} \right), \quad (5)$$

where $E_i^*(k) = (k^2 + m_i^{*2})^{1/2}$ and $\mu_i^* = \mu_i - g_{\omega i}\omega - g_{\rho i}\rho - g_{\phi i}\phi$ are the single-particle energy and the effective chemical potential for the baryons of species i, and $\gamma_i = 2$ is the spin degeneracy factor. Also, $m_i^* = -g_{\sigma i}\sigma - g_{\zeta i}\zeta - g_{\delta i}\delta$ is the effective mass of the baryons in the asymmetric hadronic medium. Parameters $g_{\sigma i}$, $g_{\zeta i}$, and $g_{\delta i}$ are fitted to reproduce the vacuum baryon masses [66]. In Eq. (4) σ_0, ζ_0, and χ_0 denote the vacuum values of the scalar fields σ, ζ, and χ, respectively.

Furthermore, we solve these equations to find the effect of the baryonic density (ρ_B), the temperature (T), the finite strangeness fraction ($f_s = \frac{\Sigma_i |s|_i \rho_i}{\rho_B}$), and the isospin asymmetric parameter ($I = -\frac{\Sigma_i I_{3i}\rho_i}{2\rho_B}$) on the σ, ζ, δ, and χ fields. Here, it is to be noted that I_{3i} is the z component of the isospin for the ith baryon, s_i is the number of strange quarks, and ρ_i is the number density of the ith baryon. For a given value of the input parameter f_s the density of different hyperons is fixed through chemical equilibrium strong reactions [66,67].

In the chiral SU(3) model, the explicit symmetry-breaking term is used to relate the light and strange quark condensates with the σ, ζ, δ, and χ fields as follows [64]:

$$\langle \bar{u}u \rangle = \frac{1}{m_u} \left(\frac{\chi}{\chi_0} \right)^2 \left[\frac{1}{2} m_\pi^2 f_\pi (\sigma + \delta) \right], \quad (6)$$

$$\langle \bar{d}d \rangle = \frac{1}{m_d} \left(\frac{\chi}{\chi_0} \right)^2 \left[\frac{1}{2} m_\pi^2 f_\pi (\sigma - \delta) \right], \quad (7)$$

and

$$\langle \bar{s}s \rangle = \frac{1}{m_s} \left(\frac{\chi}{\chi_0} \right)^2 \left(\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta, \quad (8)$$

respectively.

Furthermore, using the trace anomaly property of QCD we extract the gluon condensates in terms of the abovementioned scalar fields using [65,66]

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

In the above equation, d denotes a constant with a value of (2/11). This can be evaluated by comparing the trace of energy momentum tensor in QCD with the trace of the energy momentum tensor calculated in the chiral SU(3) model. Also, using the Euler-Lagrange equation for the Lagrangian density corresponding to the dilation field χ, we get [66]

$$T_\mu^\mu = \left\langle \frac{\beta_{\rm QCD}}{2g} G^a{}_{\mu\nu} G^{a\mu\nu} \right\rangle = -(1-d)\chi^4. \quad (10)$$

Further, we recall the QCD β function at one loop level,

$$\beta_{\rm QCD}(g) = \frac{g^3}{16\pi^2} \left(-\frac{11}{3} N_c + \frac{2}{3} N_f \right), \quad (11)$$

which for three colors ($N_c = 3$) can be written as

$$\beta_{\rm QCD}(g) = -\frac{11 g^3}{16\pi^2} \left(1 - \frac{2}{11} N_f \right). \quad (12)$$

In Eq. (12), the first term in the parentheses arises from the (antiscreening) self-interaction of the gluons, and the second term, proportional to N_f, arises from the (screening) contribution of quark pairs. Here using Eqs. (10) and (12), for the three flavors ($N_f = 3$) we can find the value of d as 2/11 [66].

III. QCD SUM RULE FOR D_0 AND D_{s0} MESONS

We now present the QCD sum rules to investigate the in-medium masses and decay constants of D_0 and D_{s0} mesons. In doing so, one starts with the two-point correlation function

$$\Pi(q) = i \int d^4x e^{iq\cdot x} \langle \mathcal{T}\{J(x)J^\dagger(0)\} \rangle_{\rho_B,T}, \quad (13)$$

where $\mathcal{T}$ is the time-ordered covariant operator, and in the present work this acts on the scalar currents for the D_0 and D_{s0} mesons, given as [7]

$$J(x) = J^\dagger(x) = \frac{\bar{c}(x)q(x) + \bar{q}(x)c(x)}{2}. \quad (14)$$

Note that in the above we consider the averaged scalar currents of particle D_0 mesons and their antiparticle $\bar{D}_0$ mesons, and thus we evaluate the averaged shift in masses and decay constants of scalar D_0 mesons and, similarly, D_{s0} mesons [44,68,69]. As mentioned earlier, we evaluate the properties of D_0 and D_{s0} mesons in isospin asymmetric matter. The finite isospin asymmetry of the medium will cause the splitting in masses of D_0^+ and D_0^0 mesons belonging to the isospin doublet of scalar D_0 mesons. In Eq. (14), for D_0^+ and D_0^0 mesons the quark field $q(x)$ is replaced by $d(x)$ and $u(x)$, respectively, whereas for D_{s0} mesons $q(x)$ is replaced by $s(x)$. The mass splitting between particles and antiparticles can be evaluated by separating the two-point correlation function into an even part and an odd part as was done in Ref. [70]. In the rest frame of nucleons, following the Fermi gas approximation, we divide the two-point correlation function into a vacuum part and nucleon- and temperature-dependent parts, i.e.,

$$\Pi(q) = \Pi_0(q) + \frac{\rho_B}{2m_N} T_N(q) + \Pi_{\rm P.B.}(q,T), \quad (15)$$

where $T_N(q)$ is the forward scattering amplitude, and ρ_B and m_N denote the total baryon density and the nucleon mass, respectively. The third term represents the thermal correlation function and is defined as [71]

$$\Pi_{\rm P.B.}(q,T) = i \int d^4x \, e^{iq\cdot x} \langle \mathcal{T}\{J(x)J^\dagger(0)\} \rangle_T, \quad (16)$$

where $\langle \mathcal{T}\{J_5(x)J_5^\dagger(0)\} \rangle_T$ is the thermal average of the time-ordered product of the scalar currents. Further, the thermal average of any operator $\mathcal{O}$ is given by [71]

$$\langle \mathcal{O} \rangle_T = \frac{\mathrm{Tr}\{\exp(-H/T)\mathcal{O}\}}{\mathrm{Tr}\{\exp(-H/T)\}}. \quad (17)$$

In the above, Tr denotes the trace over the complete set of states and H is the QCD Hamiltonian. The factor $\frac{\exp(-H/T)}{\mathrm{Tr}\{\exp(-H/T)\}}$ is the thermal density matrix of QCD. In Eq. (15), the third term corresponds to the pion bath term and has been widely used in the past to consider the effect of temperature of the medium [72,73]. Here we point out that we consider the effect of temperature at finite baryonic density on the properties of D_0 and D_{s0} mesons through the temperature dependence of the scalar fields σ, ζ, δ, and χ in terms of which scalar quark and gluon condensates are expressed, and therefore, we neglect the third term in Eq. (15). The scattering amplitude $T_N(q)$, near the pole position of the scalar meson, is represented in terms of the spectral density [68], in the limit of $\mathbf{q} \to 0$, which is parametrized in terms of three unknown parameters, a, b, and c, given as [1,13,69]

$$\begin{aligned}\rho(\omega,0) &= -\frac{f^2_{D_0/D_{s0}} m^4_{D_0/D_{s0}}}{\pi m_c^2} \mathrm{Im}\left[\frac{T_{D_0/D_{s0}}(\omega,\mathbf{0})}{(\omega^2 - m^2_{D_0/D_{s0}} + i\varepsilon)^2}\right] + \cdots \\ &= a\frac{d}{d\omega^2}\delta(\omega^2 - m^2_{D_0/D_{s0}}) + b\delta(\omega^2 - m^2_{D_0/D_{s0}}) \\ &\quad + c\theta(\omega^2 - s_0). \end{aligned} \quad (18)$$

Here, $m_{D_0/D_{s0}}$ and $f_{D_0/D_{s0}}$ are the masses and decay constants of D_0 and D_{s0} mesons and m_c denotes the mass of the charm quark. Also the first term in Eq. (18) denotes the double-pole term and exhibits the on-shell effect of the T matrix, whereas the second term represents the single-pole term and exhibits the off-shell effect of the T matrix. The third term, proportional to c, corresponds to the continuum term. Here, s_0 is the continuum threshold parameter, and its value is fixed to reproduce the vacuum masses for D_0 and D_{s0} mesons [45]. Finally, the shifts in masses and decay constants of D_0 and D_{s0} mesons from their vacuum values are given as [7,45]

$$\delta m_{D_0/D_{s0}} = 2\pi \frac{m_N + m_{D_0/D_{s0}}}{m_N m_{D_0/D_{s0}}} \rho_B a_{D_0/D_{s0}} \quad (19)$$

and

$$\delta f_{D_0/D_{s0}} = \frac{m_c^2}{2 f_{D_0/D_{s0}} m^4}\left(\frac{b\rho_B}{2m_N} - \frac{4 f^2_{D_0/D_{s0}} m^3_{D_0/D_{s0}} \delta m_{D_0/D_{s0}}}{m_c^2}\right), \quad (20)$$

respectively. Clearly, to calculate the shifts in masses and decay constants of D_0 and D_{s0} mesons we need to find the values of the unknown parameters a and b. To achieve this task, we apply the Borel transformation on the forward scattering amplitude $T_N(\omega,0)$ on the hadronic side and on the forward scattering amplitude $T_N(\omega,0)$ on the OPE side in the rest frame of the nuclear matter. After this, we equate these two equations and this leads to [7,45]

$$\begin{aligned} & a\left\{\frac{1}{M^2}\exp\left(-\frac{m^2_{D_0/D_{s0}}}{M^2}\right) - \frac{s_0}{m^4_{D_0/D_{s0}}}\exp\left(-\frac{s_0}{M^2}\right)\right\} + b\left\{\exp\left(-\frac{m^2_{D_0/D_{s0}}}{M^2}\right) - \frac{s_0}{m^2_{D_0/D_{s0}}}\exp\left(-\frac{s_0}{M^2}\right)\right\} \\ &\quad + \frac{2m_N(m_H - m_N)}{(m_H - m_N)^2 - m^2_{D_0/D_{s0}}}\left(\frac{f_{D_0/D_{s0}} m_{D_0/D_{s0}} g_{D_0/D_{s0}NH}}{m_c}\right)^2 \left\{\left(\frac{1}{(m_H - m_N)^2 - m^2_{D_0/D_{s0}}} - \frac{1}{M^2}\right)\exp\left(-\frac{m^2_{D_0/D_{s0}}}{M^2}\right) \right. \\ &\quad \left. - \frac{1}{(m_H - m_N)^2 - m^2_{D_0/D_{s0}}}\exp\left(-\frac{(m_H - m_N)^2}{M^2}\right)\right\} \\ &= +\frac{m_c\langle \bar{q}q\rangle_N}{2} \times \exp\left(-\frac{m_c^2}{M^2}\right) + \frac{1}{2}\left\{-2\left(1 - \frac{m_c^2}{M^2}\right)\langle q^\dagger i D_0 q\rangle_N + \frac{4m_c}{M^2}\left(1 - \frac{m_c^2}{2M^2}\right)\langle \bar{q} i D_0 i D_0 q\rangle_N \right. \\ &\quad \left. + \frac{1}{12}\left\langle \frac{\alpha_s GG}{\pi}\right\rangle_N\right\}\exp\left(-\frac{m_c^2}{M^2}\right). \end{aligned} \quad (21)$$

Here, m_c denotes the charm quark mass and its value is chosen to be 1.35 GeV. Further, m_H is the average mass of Λ_c and Σ_c states and in the present calculation we take its value to be 2.4 GeV. Also in the present investigation, for D_0^+ (D_0^0) and D_{s0} mesons, $\langle \bar{q}q\rangle$ is replaced by $\langle \bar{d}d\rangle$ ($\langle \bar{u}u\rangle$) and $\langle \bar{s}s\rangle$, respectively. Furthermore, as discussed earlier, we work in the heavy quark limit $q \to 0$, i.e., for D_{s0} mesons we take $m_c + m_s \approx m_c$.

A similar approach was taken in Refs. [2,74–76] to derive a Borel-transformed equation for pseudoscalar D_s mesons. This condition caused negligible impact on the results of in-medium masses and decay constants of D_s mesons [74]. In this respect we argued that the use of the heavy quark limit for D_{s0} mesons may also not have significant impact on the results of the present investigation. Moreover to find the values of the two unknown parameters a and b we differentiate the above equation with respect to $1/M^2$ to find another equation and then solve these two equations. The nucleon expectation value of the various condensates appearing in Eq. (21) is written as [2]

$$\mathcal{O}_N = [\mathcal{O}_{\rho_B} - \mathcal{O}_{\mathrm{vacuum}}]\frac{2m_N}{\rho_B}. \quad (22)$$

Explicitly, the nucleon expectation values of light quark and gluon condensates are expressed as

$$\langle u\bar{u}\rangle_N = [\langle u\bar{u}\rangle_{\rho_B} - \langle u\bar{u}\rangle_{\mathrm{vacuum}}]\frac{2m_N}{\rho_B}, \quad (23)$$

$$\langle d\bar{d}\rangle_N = [\langle d\bar{d}\rangle_{\rho_B} - \langle d\bar{d}\rangle_{\mathrm{vacuum}}]\frac{2m_N}{\rho_B}, \quad (24)$$

and

$$\left\langle \frac{\alpha_s}{\pi} G^a{}_{\mu\nu} G^{a\mu\nu} \right\rangle_N = \left[\left\langle \frac{\alpha_s}{\pi} G^a{}_{\mu\nu} G^{a\mu\nu} \right\rangle_{\rho_B} - \left\langle \frac{\alpha_s}{\pi} G^a{}_{\mu\nu} G^{a\mu\nu} \right\rangle_{\text{vacuum}} \right] \frac{2m_N}{\rho_B}. \quad (25)$$

The condensates $\langle \bar{q} g_s \sigma G q \rangle_{\rho_B}$ and $\langle \bar{q} i D_0 i D_0 q \rangle_{\rho_B}$ appearing in the Borel-transformed QCD sum rule equation are expressed in terms of light quark condensates [2,7]:

$$\langle \bar{q} g_s \sigma G q \rangle_{\rho_B} = \lambda^2 \langle \bar{q} q \rangle_{\rho_B} + 3.0\,\text{GeV}^2 \rho_B \quad (26)$$

and

$$\langle \bar{q} i D_0 i D_0 q \rangle_{\rho_B} + \tfrac{1}{8} \langle \bar{q} g_s \sigma G q \rangle_{\rho_B} = 0.3\,\text{GeV}^2 \rho_B. \quad (27)$$

The condensate $\langle q^\dagger i D_0 q \rangle_N$ is not calculated in the chiral SU(3) model and we consider its value as calculated in the linear-density approximation for our calculations. We use the values 0.18 GeV^2 ρ_B and 0.018 GeV^2 ρ_B for $\langle u^\dagger i D_0 u \rangle_N$ and $\langle s^\dagger i D_0 s \rangle_N$, respectively [77]. However, later on we see that $\langle q^\dagger i D_0 q \rangle_N$ does not affect significantly the in-medium properties of D_0 and D_{s0} mesons.

IV. $^3P_0$ MODEL

To calculate the in-medium partial decay width of $D_0 \to D + \pi$ ($D_{s0} \to D_s + \pi$), we use the $^3P_0$ model, in which the quark and antiquark pair is created in vacuum (0^{++}) [50,51].

This model had been used in literature to find the strong decays of hidden charmed states [52,53], open charmed bottom states [54,55], and bottom mesons [55–58]. In the present work of finding the two-body decay of D_0 and D_{s0} mesons, we use the transition operator as taken in Ref. [78] and find the helicity amplitude given by [79]

$$\mathcal{M}^{M_{J_{D_0}} M_{J_D} M_{J_\pi}} = \gamma \sqrt{8 E_{D_0} E_D E_\pi} \sum_{\substack{M_{L_{D_0}}, M_{S_{D_0}}, M_{L_D}, \\ M_{S_D}, M_{L_\pi}, M_{S_\pi}, m}} \langle 1m; 1-m|00\rangle \langle L_{D_0} M_{L_{D_0}} S_{D_0} M_{S_{D_0}} | J_{D_0} M_{J_{D_0}} \rangle \langle L_D M_{L_D} S_D M_{S_D} | J_D M_{J_D} \rangle$$
$$\times \langle L_\pi M_{L_\pi} S_\pi M_{S_\pi} | J_\pi M_{J_\pi} \rangle \langle \varphi_D^{13} \varphi_\pi^{24} | \varphi_{D_0}^{12} \varphi_0^{34} \rangle \langle \chi^{13}_{S_D M_{S_D}} \chi^{24}_{S_\pi M_{S_\pi}} | \chi^{12}_{S_{D_0} M_{S_{D_0}}} \chi^{34}_{1-m} \rangle I^{M_{L_{D_0}}, m}_{M_{L_D}, M_{L_\pi}}(\mathbf{k}). \quad (28)$$

In the above, $E_{D_0} = m^*_{D_0}$, $E_D = \sqrt{m_D^{*2} + K_D^2}$, and $E_\pi = \sqrt{m_\pi^{*2} + K_\pi^2}$ represent the energies of the respective mesons. Here $m^*_{D_0}$, m^*_D, and m^*_π are the in-medium masses of D_0, D, and π mesons, respectively. We then calculate the spin matrix elements $\langle \chi^{13}_{S_D M_{S_D}} \chi^{24}_{S_\pi M_{S_\pi}} | \chi^{12}_{S_{D_0} M_{S_{D_0}}} \chi^{34}_{1-m} \rangle$ in terms of the Wigner's $9j$ symbol and the flavor matrix element $\langle \varphi_D^{13} \varphi_\pi^{24} | \varphi_{D_0}^{12} \varphi_0^{34} \rangle$ in terms of the isospin of quarks as was done in Refs. [51,78,79]. In Eq. (28), $I^{M_{L_{D_0}}, m}_{M_{L_D}, M_{L_\pi}}(\mathbf{k})$ represents the spatial integral and is expressed in terms of wave functions of parent and daughter mesons. We use simple harmonic-oscillator-type wave functions defined by

$$\psi_{nLM_L} = (-1)^n (-\iota)^L R^{L+\frac{3}{2}} \sqrt{\frac{2n!}{\Gamma\left(n + L + \frac{3}{2}\right)}} \exp\left(\frac{-R^2 k^2}{2}\right) L_n^{L+\frac{1}{2}}(R^2 k^2) Y_{lm}(\mathbf{k}). \quad (29)$$

Here, R is the radius of the meson, $L_n^{L+\frac{1}{2}}(R^2 k^2)$ represents the associated Laguerre polynomial, and $Y_{lm}(\mathbf{k})$ denotes the spherical harmonic function.

By taking these calculations in hand and following the Jacob-Wick formula, we transform the helicity amplitude into the partial-wave amplitude as follows:

$$\mathcal{M}^{JL}(D_0 \to D\pi) = \gamma \frac{\sqrt{2 E_{D_0} E_D E_\pi}}{6\sqrt{3}} [I_0 - 2I_1], \quad (30)$$

where

$$I_0 = -4 \frac{\sqrt{3}}{\pi^{5/4}} \frac{R_{D_0}^{5/2} R_D^{3/2} R_\pi^{3/2}}{\left(R_{D_0}^2 + R_D^2 + R_\pi^2\right)^{5/2}} \left[1 - \mathbf{k}_D^2 \frac{\left(2R_{D_0}^2 + R_D^2 + R_\pi^2\right)\left(R_D^2 + R_\pi^2\right)}{4\left(R_{D_0}^2 + R_D^2 + R_\pi^2\right)}\right] \exp\left[-\frac{\mathbf{k}_D^2 R_{D_0}^2 \left(R_D^2 + R_\pi^2\right)}{8\left(R_{D_0}^2 + R_D^2 + R_\pi^2\right)}\right] \quad (31)$$

and

$$I_1 = 4 \frac{\sqrt{3}}{\pi^{5/4}} \frac{R_{D_0}^{5/2} R_D^{3/2} R_\pi^{3/2}}{\left(R_{D_0}^2 + R_D^2 + R_\pi^2\right)^{5/2}} \exp\left[-\frac{\mathbf{k}_D^2 R_{D_0}^2 \left(R_D^2 + R_\pi^2\right)}{8\left(R_{D_0}^2 + R_D^2 + R_\pi^2\right)}\right]. \quad (32)$$

We then finally calculate the decay width using

$$\Gamma = \pi^2 \frac{|\mathbf{k}_D|}{m_A^2} \sum_{JL} |\mathcal{M}^{JL}|^2, \quad (33)$$

where γ is the strength of the pair creation in the vacuum and its value is taken as 6.74 [79]. Also, $|\mathbf{k}_D|$ represents the momentum of the D and π mesons in the rest mass frame of the D_0 mesons and is given by

$$|\mathbf{k}_D| = \frac{\sqrt{\left[m_{D_0}^{*2} - (m_D^* - m_\pi^*)^2\right]\left[m_{D_0}^{*2} - (m_D^* + m_\pi^*)^2\right]}}{2m^*_{D_0}}. \quad (34)$$

Here, for the decay $D_{s0} \rightarrow D_s\pi$, the values for D_0 are replaced by D_{s0} and D with D_s. Thus, through the in-medium mass of D_0 and D_{s0}, D and D_s, and π mesons, the in-medium partial decay widths of the processes $D_0 \rightarrow D\pi$ and $D_{s0} \rightarrow D_s\pi$ can be calculated.

V. RESULTS AND DISCUSSION

This section elaborates the results of the present investigation. We use the nuclear saturation density, $\rho_0 = 0.15$ fm^{-3}; the average values of coupling constants for scalar D_0 and D_{s0} mesons, $g_{D_0/D_{s0}N\Lambda_\pi} \approx g_{D_0/D_{s0}N\Sigma_\pi} \approx 6.74$; and the values of the continuum threshold parameter s_0 for D_0^+, D_0^0, and D_{s0} mesons: 8, 8, and 7 GeV^2, respectively. Here, we point out that due to the unavailable data for the exact $g_{D_0/D_{s0}N\Sigma_\pi}$, we consider the same value of the couplings $g_{DN\Lambda_\pi} \approx g_{D_0N\Lambda_\pi}$, which was calculated using QCD sum rules [80]. Also, later on we show that the uncertainties in the values of $g_{D_0/D_{s0}N\Sigma_\pi}$ will not cause significant impact on the results of the present investigation. Therefore, we consider $g_{D_0/D_{s0}N\Lambda_\pi} \approx g_{D_0/D_{s0}N\Sigma_\pi} \approx 6.74$ [45]. Further, the vacuum values of masses of D_0^+, D_0^0, and D_{s0} mesons are taken as 2.355, 2.350, and 2.317 GeV, whereas the vacuum values of decay constants are taken to be 0.334, 0.334, and 0.333 GeV, respectively. We represent the shift in masses and decay constants of D_0^+, D_0^0, and D_{s0} mesons as a function of the squared Borel mass parameter, M^2. To find the shift in masses and decay constants of D_0^+, D_0^0, and D_{s0} mesons we choose a proper Borel window within which the least variation in the masses and decay constants is observed. We choose the Borel window for D_0 and D_{s0} mesons to be 5–9 GeV^2.

A. Shifts in masses and decay constants

In Fig. 1 (Fig. 2) we represent the shift in masses (decay constants) of the isospin doublet of scalar D_0 mesons, whereas in Fig. 3 we plot the shifts in masses and decay constants of D_{s0} mesons in an isospin asymmetric hot and dense strange hadronic medium as a function of the squared Borel mass parameter M^2. In Table I we give the numerical values of shifts in masses and decay constants of these mesons. Here, in the present investigation, we notice an enhancement in the masses, whereas there is a drop in the values of decay constants of scalar D_0 and D_{s0} mesons in nuclear matter as well as in the strange hadronic matter. Moreover, for any given value of the isospin asymmetric parameter I, the strangeness fraction f_s, and the temperature T of the medium, the magnitude of the enhancement (drop) in the values of masses (decay constants) of D_0 and D_{s0} mesons increases as a function of the baryonic density of the medium. For example, in symmetric nuclear medium, at temperature $T = 0$ and baryonic density $\rho_B = \rho_0$, the masses (decay constants) of D_0^0, D_0^+, and D_{s0} mesons increase (decrease) by 3.7% (2.9%), 2.7% (2.2%), and 3.5% (2.3%), respectively, from their vacuum values. Further, at baryonic density $4\rho_0$ of the same medium, the above values of percentage increase (decrease) change to 6.8% (5.8%), 5.3% (4.3%), and 6.8% (4.2%), respectively.

We observe similar behavior for the shifts in masses and decay constants of the above mesons at the finite strangeness fraction f_s. For example, in a symmetric strange hadronic medium at strangeness fraction $f_s = 0.3$, the values of the masses (decay constants) of D_0^0, D_0^+, and D_{s0} mesons increase (decrease) by 4.5% (3.5%), 3.3% (2.6%), and 4.4% (2.7%), respectively from their vacuum values, at $\rho_B = \rho_0$ and temperature $T = 0$. With further increase in the strangeness fraction parameter to $f_s = 0.5$, the above percentage values change to 4% (3.2%), 3% (2.6%), and 4.8% (3.3%), at $\rho_B = \rho_0$ and temperature $T = 0$. Likewise, at baryonic density $4\rho_0$, and $f_s = 0.3$, these percentage values further enhance to 7.5% (5.6%), 5.7%(4.2%), and 9%(5%), respectively. Furthermore, at baryonic density $4\rho_0$, and $f_s = 0.5$, these values shift to 7% (5.9%), 5.3%(4.4%), and 10%(6.3%), respectively. Here we observe a small amount of decrease (increase) in the values of

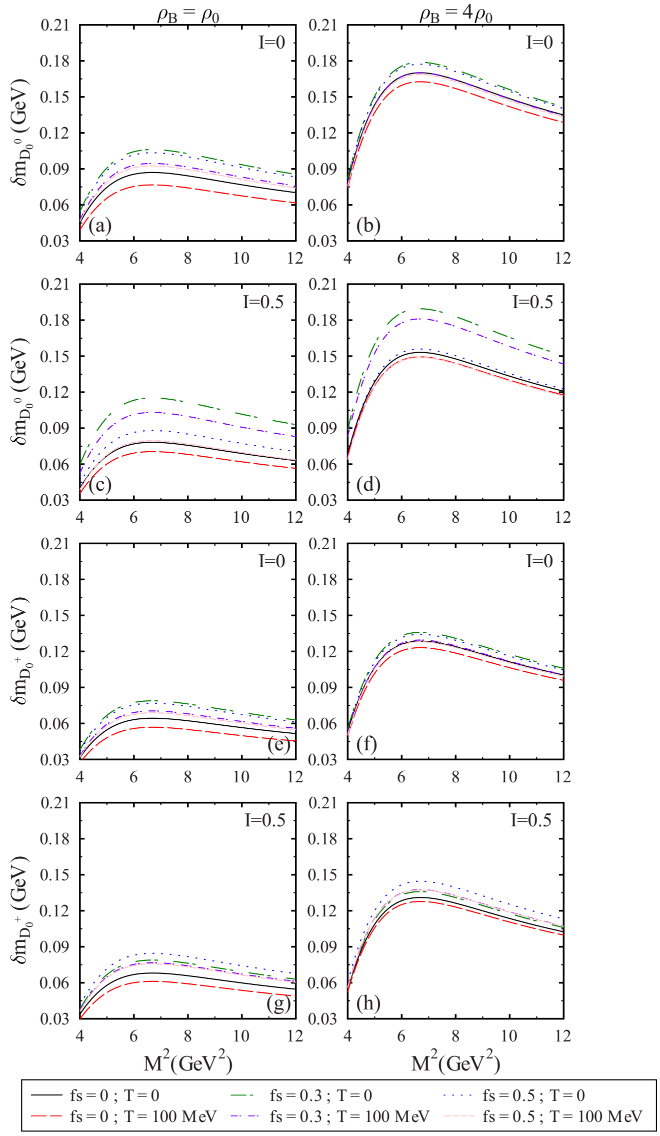

FIG. 1. Variation of shifts in masses of scalar D_0^0 and D_0^+ mesons as a function of the squared Borel mass parameter M^2 for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV, and strangeness fractions $f_s = 0$, 0.3, and 0.5. The results are given at baryonic densities ρ_0 and $4\rho_0$.

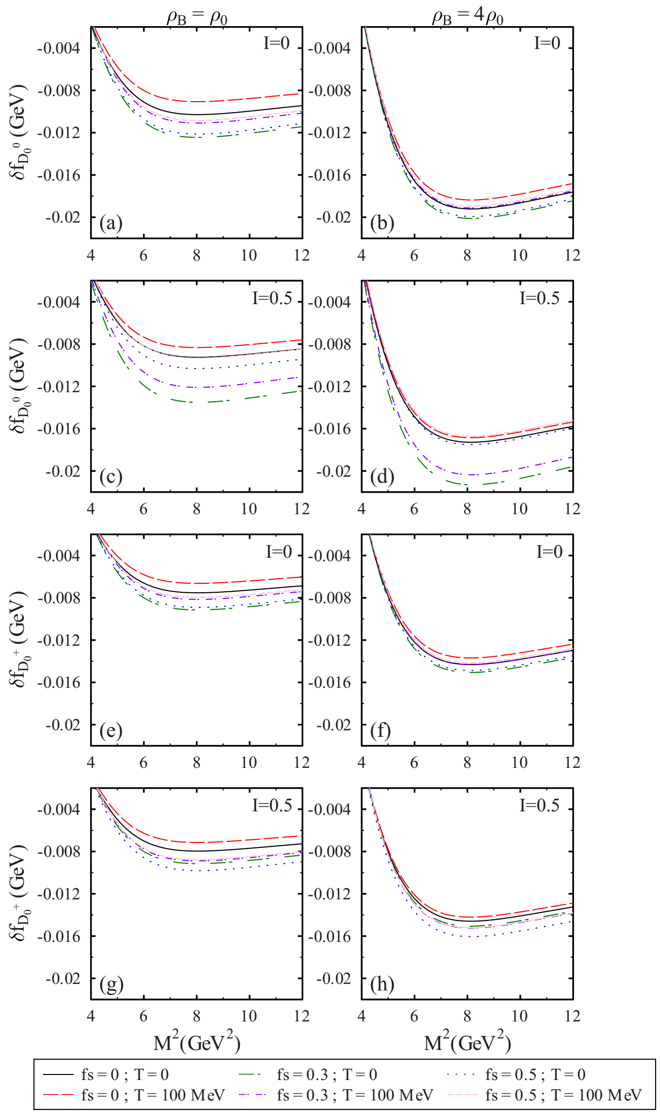

FIG. 2. Variation of shifts in decay constants of scalar D_0^0 and D_0^+ mesons as a function of the squared Borel mass parameter M^2 for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV, and strangeness fractions $f_s = 0$, 0.3, and 0.5. The results are given at baryonic densities ρ_0 and $4\rho_0$.

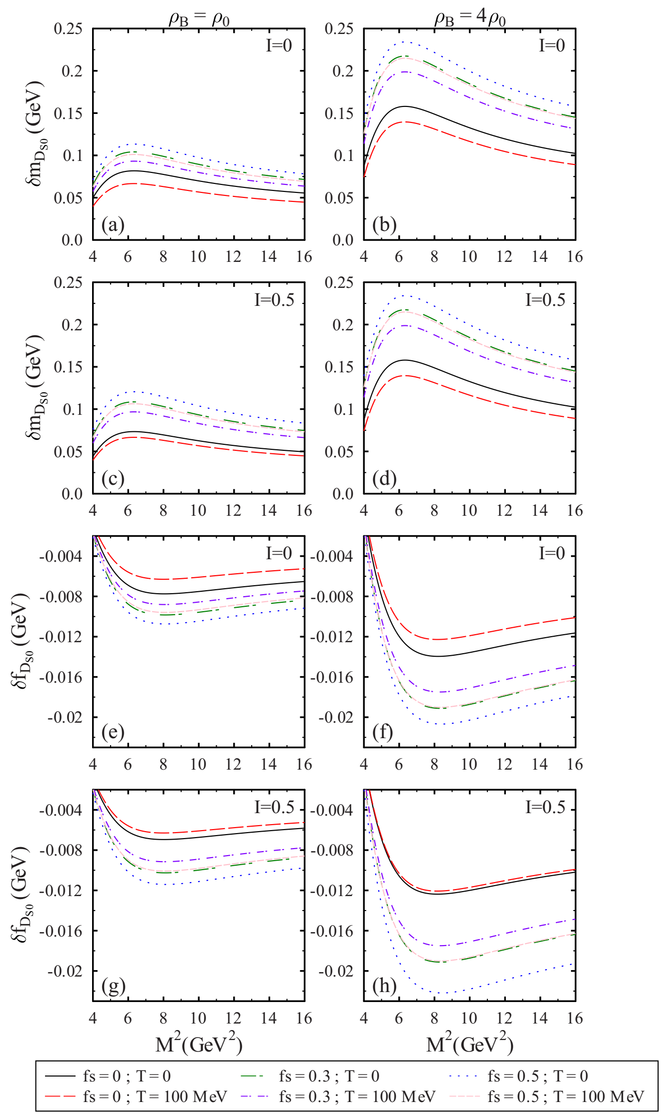

FIG. 3. Variation of shifts in masses and decay constants of scalar D_{s0} mesons as a function of the squared Borel mass parameter M^2 for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV, and strangeness fractions $f_s = 0$, 0.3, and 0.5. The results are given at baryonic densities ρ_0 and $4\rho_0$.

the masses (decay constants) of D_0^0 mesons as we move from $f_s = 0.3$ to $f_s = 0.5$. This can be understood on the basis that the magnitude of the σ field first decreases upon moving from $f_s = 0$ to 0.3 and then increases as we further increase from $f_s = 0.3$ to 0.5. Moreover, we notice that the shifts in masses and decay constants of D_{s0} mesons are more sensitive to the finite strangeness fraction in the medium as compared to the nonstrange D_0 mesons. This can be understood on the basis that the in-medium mass and decay shifts of D_0 mesons depend upon the light quark condensate $\langle\bar{q}q\rangle$, whereas for D_{s0} mesons they are evaluated using the strange quark condensate $\langle\bar{s}s\rangle$. As can be seen from Eq. (8), the strange quark condensate $\langle\bar{s}s\rangle$ is proportional to the strange scalar field ζ which is more sensitive to the strangeness fraction of the medium as compared to the nonstrange scalar field σ.

The effect of finite temperature on the mass and decay shifts of the abovementioned mesons is observed to be opposite to that of the strangeness fraction. For example, at finite-temperature medium, i.e., $T = 100$ MeV, we observe the percentage values of increase (drop) in the masses (decay constants) of D_0^0, D_0^+, and D_{s0} mesons to be 6.7% (5%), 5.1% (3.7%), and 9% (5.7%), respectively, from their vacuum values at $\rho_B = 4\rho_0$, $f_s = 0.5$, and $I = 0$. Evidently, these percentage values are lower than the values 7% (5.2%), 5.3% (3.9%), and 10% (6.2%), respectively, observed in the same medium but at zero temperature. Therefore, finite temperature of the medium causes decreases in the masses and increases in the values of decay constants of D_0^0, D_0^+, and D_{s0} mesons.

TABLE I. Values of shifts in masses and decay constants of D_0^0, D_0^+, and D_{s0} mesons (in units of MeV).

	f_s	$I=0$				$I=0.5$			
		$T=0$		$T=100$ MeV		$T=0$		$T=100$ MeV	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
$\delta m_{D_0^0}$	0	87	162	76	156	78	148	72	143
	0.3	106	178	94	170	115	189	103	181
	0.5	103	171	93	162	87	150	80	145
$\delta m_{D_0^+}$	0	64	125	58	120	68	127	62	123
	0.3	78	136	70	129	78	136	76	137
	0.5	76	129	69	123	84	139	79	145
$\delta m_{D_{s0}}$	0	81	158	67	140	73	140	66	137
	0.3	104	217	93	198	108	217	96	198
	0.5	113	234	101	214	120	252	106	224
$\delta f_{D_0^0}$	0	−10	−19.4	−9	−18.6	−9.2	−17.5	−8.3	−17.1
	0.3	−11.8	−19	−10.6	−18	−12.9	−20	−11.6	−19
	0.5	−11	−20	−10.8	−19.2	−10.3	−17.7	−9.3	−16.9
$\delta f_{D_0^+}$	0	−7.5	−14.4	−6.6	−13.9	−7.9	−14.7	−7.1	−14.4
	0.3	−8.7	−14	−7.8	−13.5	−8.7	−14	−8.5	−14
	0.5	−8.9	−15	−7.9	−14.3	−9.8	−16.2	−8.7	−15.4
$\delta f_{D_{s0}}$	0	−7.7	−14	−6.3	−12	−7	−12.5	−6.3	−12
	0.3	−9	−17	−8.2	−15.9	−9.5	−17	−8.5	−16
	0.5	−11	−21	−9.6	−19	−11.5	−22.7	−10	−20.4

The finite isospin asymmetry of the medium causes the splitting in the in-medium masses of D_0^0 and D_0^+ mesons. For example, in cold nuclear medium, at baryon density $\rho_B=\rho_0$, if we change the isospin asymmetry parameter from $I=0$ to 0.5, the values of masses and decay constants of D_0^0 (D_0^+) mesons decrease (increase) by 0.3% (0.15%) and 0.25% (0.1%), respectively. At higher baryonic density, $4\rho_0$, the above percentage values shift to 0.5% (0.2%) and 0.6% (0.09%), respectively. The change in isospin asymmetry of the medium also affects the in-medium masses of scalar D_{s0} mesons. For example, at baryonic density ρ_0 upon shifting from $I=0$ to 0.5, we observed a 0.3% (0.1%) decrease in the value of the mass (decay constant) of D_{s0} mesons at $T=0$ and $f_s=0$. These percentage values further increase to 0.7% (0.47%) at higher baryonic density $4\rho_0$.

In Ref. [49], we observed a negative shift in the masses of pseudo-scalar D mesons using the chiral SU(3) model and QCD sum rules. The opposite shift in the masses of scalar D_0 and pseudoscalar D mesons is due to the opposite sign with the term $\frac{m_c\langle\bar{q}q\rangle_N}{2}$ Eq. (21), present in the Borel-transformed equation (also see Eq. (19) of Ref. [49]). This causes negative and positive values of the unknown parameter a [13], calculated for scalar D_0^0 and pseudoscalar D mesons, respectively. This further causes positive and negative values of the scattering length for D_0^0N and D^0N scattering, respectively. In Fig. 4 we show the variation of scattering length corresponding to scattering of D_0^0 and D^0 mesons with nucleons as a function of the baryonic density for isospin asymmetric parameters $I=0$ and 0.5, in cold nuclear medium.

Moreover, to understand more about the extent of isospin and flavor symmetry breaking in the medium, in Fig. 5 we plot the ratio of in-medium decay constants of $f^*_{D_0}/f^*_{D_+}$ [panel (a)], $f^*_{D_{s0}}/f^*_{D^+}$ [panel (b)], and $f^*_{D_{s0}}/f^*_{D^0}$ [panel (c)] as a function of the baryonic density at $T=0$. As expected, the ratio $f^*_{D_0^0}/f^*_{D^+}$ is more sensitive to the isospin asymmetry of the medium as compared to the strangeness fraction. The opposite is true for the in-medium ratios of $f^*_{D^0_{s0}}/f^*_{D^0}$ and $f^*_{D^0_{s0}}/f^*_{D^+}$.

Here we point out that we divide the two-point correlation function using the linear-density approximation; however, we use the condensates calculated through the self-consistent SU(3) mean-field model. To check its consistency at higher values of baryonic density, in Fig. 6 we compare the in-medium behavior of the light quark condensates $\langle\bar{d}d\rangle_{\rho_B}$ ($\langle\bar{s}s\rangle_{\rho_B}$) and the in-medium mass of D_0^+ (D_{s0}) mesons (in symmetric nuclear medium), both are calculated using the linear-density approximation and the chiral SU(3) model. Within the linear-density approximation, the light quark condensate $\langle\bar{d}d\rangle_{\rho_B}$, is calculated using $\langle d\bar{d}\rangle_{\rho_B}=\langle d\bar{d}\rangle_0+\frac{\sigma_N\rho_B}{m_u+m_d}$, whereas the strange quark condensate is calculated using $\langle\bar{s}s\rangle_{\rho_B}=0.8\langle\bar{q}q\rangle_0+y\frac{\sigma_N\rho_B}{m_u+m_d}$, for $\sigma_N=45$ MeV and $m_u+m_d=11$ MeV [2,13]. Here the

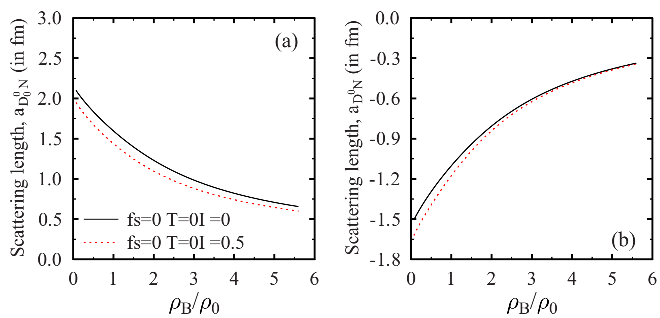

FIG. 4. Variation of the scattering length (in fm) of scalar and pseudoscalar D mesons with nucleons in nuclear medium.

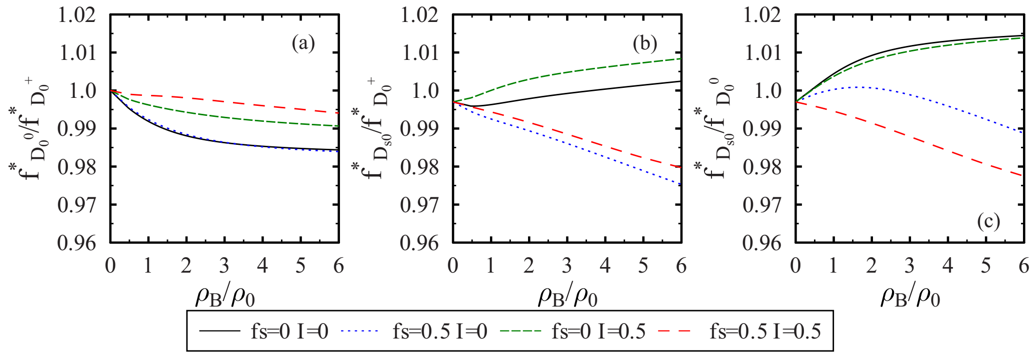

FIG. 5. Variation of ratio of in-medium decay constants $\frac{f^*_{D^0_0}}{f^*_{D^+_0}}$, $\frac{f^*_{D_{s0}}}{f^*_{D^+}}$, and $\frac{f^*_{D_{s0}}}{f^*_{D^0}}$ as a function of the baryonic density of the medium.

term $\langle\bar{q}q\rangle_0$ is the vacuum value of the light quark condensate and is given as $(-0.245\ \text{GeV})^3$. Also, the value of y is taken to be 0.5. In addition, we calculate the masses of D_0^+ (D_{s0}) mesons by considering only the condensate $\langle\bar{d}d\rangle_{\rho_B}$ ($\langle\bar{s}s\rangle_{\rho_B}$) in QCD sum rule equations, which we calculate using the linear-density approximation at zero temperature and in symmetric nuclear medium. The linear behavior of light quark and strange condensates is reflected in the linear variation of masses of D_0^+ and D_{s0} mesons. However, if we calculate $\langle\bar{d}d\rangle_{\rho_B}$ ($\langle\bar{s}s\rangle_{\rho_B}$) using the chiral SU(3) model, then we observe a nonlinear decrease as a function of the baryonic density of the medium. Similarly, corresponding in-medium masses of D_0^+ (D_{s0}) mesons increase nonlinearly as a function of the baryonic density. Moreover, the observed nonlinear decrease of the light quark condensate $\langle\bar{d}d\rangle_{\rho_B}$ at higher baryonic density of the medium, calculated using the chiral SU(3) model, is in accordance with the work of Kaiser *et al.* [81] and Li and Ko [82]. In this work, the authors calculated the light quark condensates beyond the linear-density approximation using chiral perturbation theory. Therefore, the use of the chiral SU(3) model to calculate the light quark condensates enables us to investigate the in-medium mass and decay constants of D_0 and D_{s0} mesons at higher baryonic density of the medium using QCD sum rules. Additionally, in Fig. 6 we show the effect of a 10% change in the value of σ_N on the results of the present investigation. We notice that, a 10% increase in the value of σ_N causes a decrease in the magnitude of the quark condensates. This further causes an increase in the values of the masses of D_0^+ and D_{s0} mesons. Further, a 10% decrease in the value of σ_N causes an increase in the magnitude of quark condensates, which further causes a decrease in the masses of D_0^+ and D_{s0} mesons.

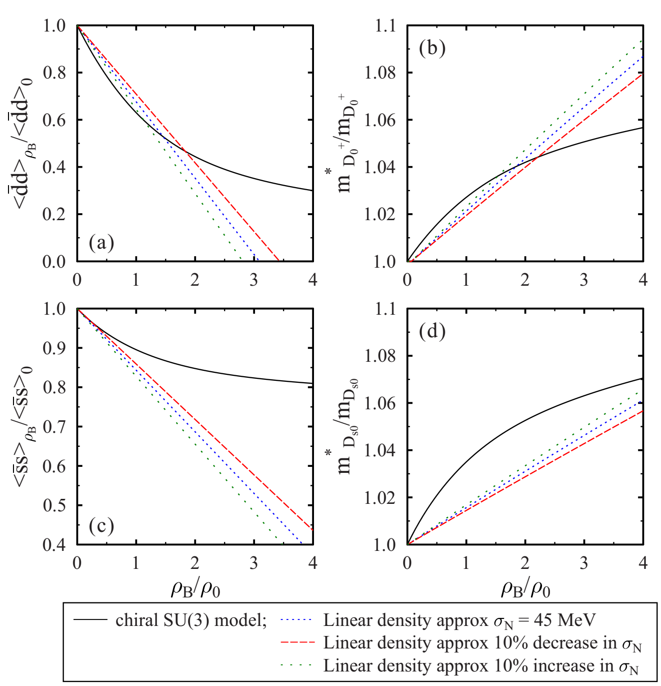

FIG. 6. Variation of in-medium mass of scalar D_0 and D_{s0} mesons and corresponding light quark and strange quark condensates [calculated using the linear-density approximation and the chiral SU(3) model] as a function of the baryonic density of the medium.

Additionally, we notice that the inclusion of the next-to-leading-order term (NLO) to the scalar quark condensates $\langle\bar{q}q\rangle$ in QCD sum rules [Eq. (21)] enhances the magnitude of the shift in the mass of the abovementioned meson [13]. Further, we notice a major contribution of the scalar quark condensates $\langle\bar{q}q\rangle$ to the shifts in the masses of scalar D_0 and D_{s0} mesons as compared to the all other condensates. To understand this, we tabulate the numerical values of shifts in the masses of D_0^+ and D_0^0 mesons in Tables II and III, respectively. We also notice that the condensate $\langle\bar{q}iD_0q\rangle_N$, which we do not calculate from

TABLE II. Mass shifts of D_0^+ mesons (in MeV) are compared by considering the contribution of individual condensates.

D_0^+		$I=0$				$I=0.5$			
		$T=0$		$T=100$		$T=0$		$T=100$	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
All condensates	NLO	83	142	78	140	87	145	82	141
	LO	64	125	58	120	68	127	62	123
$\langle\bar{d}d\rangle_N \neq 0$	NLO	84	145	78	141	89	149	80	143
	LO	63	132	56	126	66	134	60	131
$\langle\bar{q}iD_0q\rangle_N = 0$	NLO	86	151	81	146	93	155	84	146
	LO	66	138	59	132	70	140	63	137

TABLE III. Mass shifts of D_0^0 mesons (in MeV) are compared by considering the contribution of individual condensates.

D_0^0		$I=0$				$I=0.5$			
		$T=0$		T=100		$T=0$		T=100	
		ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$	ρ_0	$4\rho_0$
All condensates	NLO	103	181	95	170	91	166	88	164
	LO	87	162	76	156	78	148	72	143
$\langle\bar{u}u\rangle_N \neq 0$	NLO	105	178	97	168	93	164	90	161
	LO	85	173	75	165	77	156	69	153
$\langle\bar{q}iD_0q\rangle_N = 0$	NLO	104	184	92	179	99	171	89	167
	LO	89	180	79	173	81	164	73	160

the chiral SU(3) model, has an insignificant contribution to the shifts in masses of the above-studied charmed mesons.

The uncertainties in the results of the present calculations may arise because of the medium modification in the coupling constants $g_{D_0/D_{s0}N\Lambda_\pi}$ and $g_{D_0/D_{s0}N\Sigma_\pi}$ and the continuum threshold parameter s_0. In the present work, we neglect their in-medium modification. However, in symmetric nuclear medium, if we allow a decrease in the value of the coupling constant (continuum threshold parameter) by 5%, then the shift in the mass of the D_0^0 meson decreases (increases) by 1.5% (15%) at baryonic density ρ_0 and temperature $T = 0$. Likewise, the magnitude of the shift in the decay constant decreases (decreases) by 0.5% (10%). Further, in nuclear medium and at baryonic density $4\rho_0$, the shift in the mass and the decay constant of the D_0^0 meson decreases (increases) by 1.6%(17%) and 0.58%(11%), respectively. This indicates that the errors caused by the shift in the value of the coupling constant (continuum threshold parameter) may have a insignificant (significant) effect on the shifts in the masses and decay constants of D_0 and D_{s0} mesons. Apart from this the variation in the Borel window also has a significant impact on the results of the present investigation; for example, if we shift our Borel window M^2 from 5–9 to 9–12, then we find a 15% (30%) change in the values of the mass (decay constant) of the D_0^0 meson at $\rho_B = \rho_0$ and temperature $T = 0$. Likewise at baryonic density $4\rho_0$ the above values shift to 16% (7%). Therefore proper care should be taken to choose a suitable Borel window.

Now, we compare the results of the present investigation with the available data on medium modification of scalar D_0 mesons. It should be noted that no work is available in literature within any model that calculates the masses and the decay constants of scalar D_0 and D_{s0} mesons in strange hadronic matter. In Ref. [45], Wang and Huang applied the linear-density QCD sum rule and calculated the positive shift of 69 MeV for D_0 mesons in cold symmetric nuclear matter. In Ref. [13] by adding the next-to-leading-order term in the QCD sum rules, Wang found the shifts in the mass and the decay constant of the D_0 meson to be 80 and 11 MeV accordingly in cold and symmetric nuclear matter. Furthermore, an extra widening of the large width of the scalar D_0 mesons and a width of nearly 100 MeV was observed for the case of the D_{s0} meson in normal nuclear matter by using the coupled-channel approach [3]. In Ref. [2], Hilger *et al.* observed the mass splitting between D_0 and $\bar{D}_0$ mesons by dividing the even and odd terms of the correlation function in nuclear matter. However, in the present work, as mentioned earlier, we observe average mass shifts of D_0 and $\bar{D}_0$ mesons by taking the average particle and antiparticle currents. Further, we point out that in all these studies the calculations were done in nuclear medium and the results were limited to only nuclear saturation density $\rho_B = \rho_0$. On the other hand, as mentioned earlier, the use of the mean-field SU(3) model enabled us to investigate the results beyond the normal nuclear density. Furthermore, the in-medium properties of D_0 and D_{s0} mesons have been evaluated in an isospin asymmetric and strange hadronic medium at finite temperature. In this sense, upon comparison with the available data the present study is one step forward. The results of the enhancement in the masses of scalar D_0 and D_{s0} mesons suggest to us that scalar mesons may not cause the J/ψ suppression in the HIC experiments and one might think that these enhanced masses of D_0 mesons may act as facilitators in the production of the J/ψ state in heavy-ion collision experiments. Further, the enhanced masses of scalar D_0 mesons indicate the repulsive interactions of D_0 mesons with nucleons as well as with hyperons, and therefore, the formation of scalar D_0 meson-nucleon and -hyperon bound states may not be possible.

From the application point of view, the study of in-medium masses of open charmed mesons can be useful in understanding the possible outcomes of future heavy-ion collision experiments. Particularly in the PANDA experiment, open charm mesons can be created by tuning the antiproton energy to that higher charmonium state which decays to these mesons. Then D mesons may interact with the nucleons and in this sense prior knowledge of in-medium masses of open charm mesons may be useful to understand these interactions [83]. Further, the study of in-medium properties of the open charm mesons may also be useful in the precise theoretical calculations of their elliptic flow and the nuclear modification factor of open charm mesons in a region relevant to FAIR [42]. In Ref. [84], Paryeva *et al.* theoretically calculated the momentum-dependent experimental observables, i.e., transparency ratio and absolute and relative charmonium yields of J/ψ mesons. In these calculations, the authors observed the possible impact of the in-medium mass of the J/ψ state on these experimental observables. In similar kinds of calculations for the experimental observables of open charm mesons the use of their in-medium masses may have significant impact. Furthermore, one may also use these in-medium properties of open charm mesons in the precise calculation of cross sections of reactions where charm production is observed by the pion beam on a proton target as done in Refs. [85,86]. The in-medium masses of open charmed strange and nonstrange D mesons calculated in the present work can be used for example in statistical hadronization models [15] and production ratio $\frac{D_{s0}}{D_0}$ can be calculated and can be compared in the future with experimental results. The medium that may be produced in the FAIR project will be at high baryonic density in contrast to the ultrarelativistic heavy-ion collisions of the RHIC and LHC experiments where medium with $\rho_B \approx 0$ and high temperature is produced. The properties of D mesons calculated at finite baryonic density ρ_B and moderate temperature will be very different as compared to those calculated at $\rho_B = 0$, and hence the experimental observables will also be very different. For example, in the present work we calculated the medium modification of D mesons at finite density using scalar fields and condensates. The behavior of these fields and condensates at finite density and finite temperature is significantly different as compared to their behavior in the zero density and finite temperature case. For example, as was discussed in detail in Ref. [65], at $\rho_B = 0$, the magnitude of scalar fields σ, ζ, and χ decreases with an increase in temperature, whereas at finite ρ_B the magnitude of these scalar fields first increases with an increase in temperature and then decreases above a certain value of temperature that is density dependent. Thus, a detailed analysis must be done before making final conclusions about experimental observables using theoretical calculations for FAIR and LHC energies.

B. In-medium partial decay widths of D_0^0 (D_0^+) and D_{s0} mesons

In this section, using the $^3P_0$ model, we calculate the in-medium partial decay width of the scalar D_0^+, D_0^0, and D_{s0} mesons for the processes $D_0^+ \rightarrow D^+ + \pi$, $D_0^0 \rightarrow D^0 + \pi$, and $D_{s0} \rightarrow D_s + \pi$, respectively. In Fig. 7, we represent the partial decay widths $\Gamma_{D^+\pi}(D_0^+)$ and $\Gamma_{D^0\pi}(D_0^0)$, whereas in Fig. 8 we present $\Gamma_{D_s\pi}(D_{s0})$ as a function of R_A values (here R_A represents the harmonic oscillator radius of the parent meson wave function). Here, as mentioned earlier, to calculate the in-medium partial decay width for the abovementioned processes, we consider the medium modified masses of parent as well as daughter mesons. In above-listed decay processes daughter mesons are pseudoscalar, whereas parent mesons are scalar. For the in-medium mass of pseudoscalar D and D_s mesons, we follow our earlier work [49], where calculations were done using QCD sum rules and the chiral SU(3) model. Also, we include the medium modified mass of the π meson, calculated using chiral perturbation theory [63]. In Ref. [63], Goda and Jido studied the in-medium mass of π mesons in symmetric nuclear matter at zero temperature including next-to-leading-order terms up to baryonic density $3\rho_0$. Because no work is currently available on the study of the mass shift of π mesons in asymmetric strange matter at finite temperatures, we use the same shift in mass for the isospin asymmetric strange hadronic matter also.

The effect of in-medium modifications of parent and daughter mesons is observed to be significant on the partial decay width of D_0 and D_{s0} mesons. From Figs. 7 and 8, we notice an enhanced in-medium partial decay width for decays $D_0^+ \rightarrow D^+ + \pi$, $D_0^0 \rightarrow D^0 + \pi$, and $D_{s0} \rightarrow D_s + \pi$ as compared to the vacuum values. Moreover, we do not observe any node in the abovementioned partial decay widths since the parent and daughter mesons are in their ground states. Also, from Eqs. (28), (33), and (30) we note that the value of the partial decay width is proportional to the square of the decay amplitude, which is further dependent on the spatial integral. Furthermore, this spatial integral has been solved analytically for the respective decay channel [Eqs. (31) and (32)], and therefore, the behavior of the partial decay width is the resulting effect of the two integrals I_0 and I_1 occurring in Eq. (30). Here through the competitive effect of the two

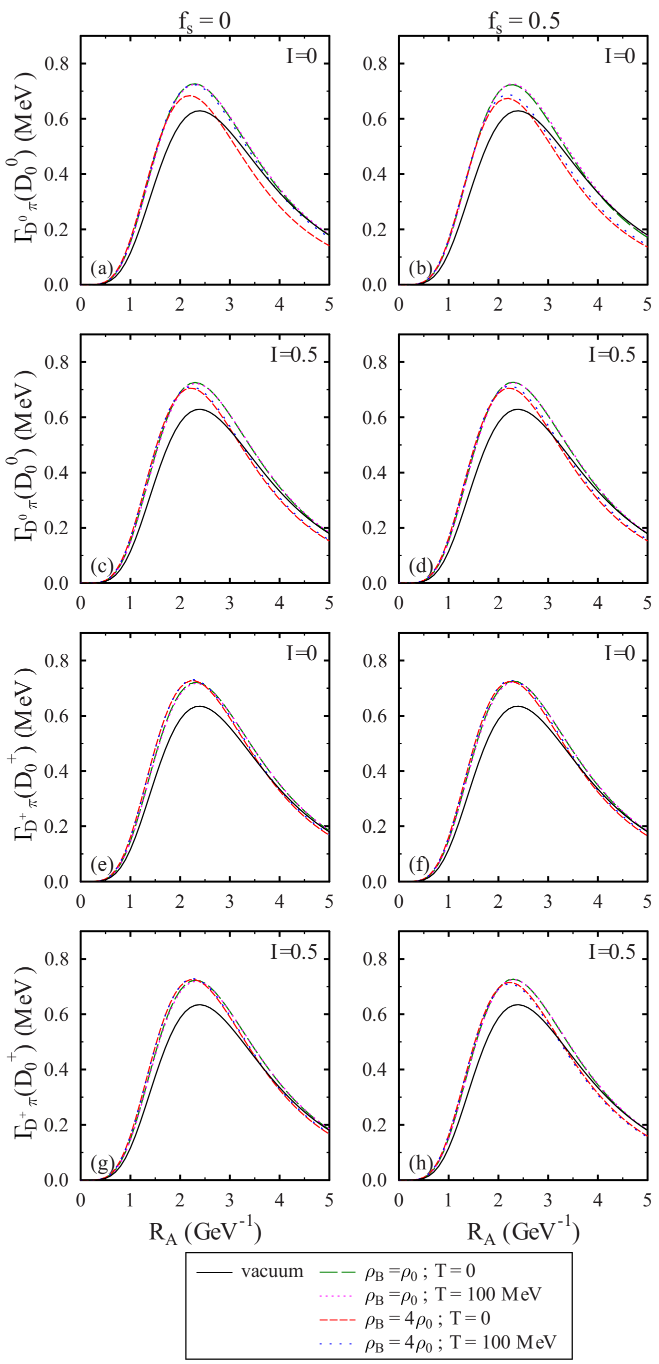

FIG. 7. Variation of the partial decay widths of the particular decays $D_0^+ \rightarrow D^+ + \pi$ and $D_0^0 \rightarrow D^0 + \pi$ as a function of the R_A value (in GeV^{-1}).

integrals we observe the vacuum values of partial decay widths $\Gamma_{D^+\pi}(D_0^+)$, $\Gamma_{D^0\pi}(D_0^0)$, and $\Gamma_{D_s\pi}(D_{s0})$ to be 557, 551, and 374 keV, respectively, at $R_A = 1.89\ \text{GeV}^{-1}$ values. However, in symmetric nuclear medium, at $\rho_B = \rho_0$ and $T = 0$, the above values are observed to be 666, 653, and 544 keV, respectively.

Furthermore, upon moving from symmetric nuclear medium ($f_s = 0$) to strange medium ($f_s = 0.5$), we observe enhancement in the respective values of the partial decay width

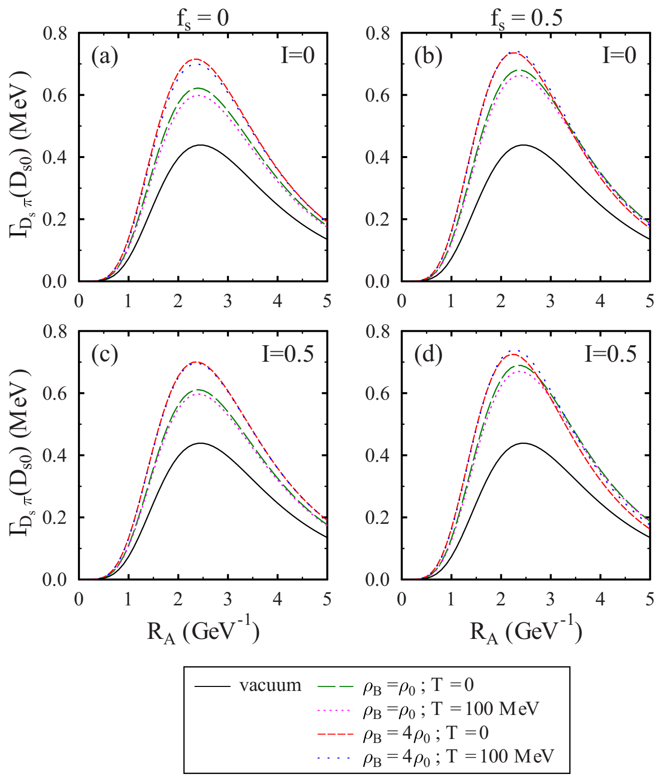

FIG. 8. Variation of the partial decay widths of a particular decay $D_{s0} \rightarrow D_s + \pi$ as a function of the respective R_A value (in GeV^{-1}).

and the above-listed values change to 669, 661, and 604 keV, respectively, at $\rho_B = \rho_0$ and $T = 0$. Here, we note that the in-medium mass of the D_{s0} meson is sensitive to the finite strangeness fraction, and therefore, the increase in the value of $\Gamma_{D_s\pi}(D_{s0})$ is more as compared to $\Gamma_{D^+\pi}(D_0^+)$ and $\Gamma_{D^0\pi}(D_0^0)$ in symmetric strange hadronic matter. On the other hand, upon increasing the temperature of the symmetric nuclear matter, the abovementioned partial decay widths are observed to be 660, 647, and 521 keV, respectively, at normal nuclear matter density. Furthermore, upon moving from symmetric nuclear matter ($I = 0$) to asymmetric nuclear matter ($I = 0.5$) the abovementioned values shift to 662, 656, and 533 keV, respectively, for the nuclear saturation density and zero temperature situation. Moreover, if we consider $D_{s0}(2317)$ mesons decaying to $D_s + \pi$ mesons through η-π^0 mixing [87], then the observed vacuum values of the partial decay width was just 32 keV. Further, in normal nuclear matter density, ρ_0, and in cold symmetric nuclear medium, considering the mixing effect, the observed partial decay width increases to 48 keV. This is because of the enhanced decay channel caused by increases (decreases) in the masses of $D_{s0}(D_s)$ mesons. Also, upon addition of hyperons along with nucleons, at $\rho_B = \rho_0$ and $T = 0$, the decay width further increases to 56 keV. We now compare the results of the in-medium decay width with those of previous works. As far as our knowledge regarding the literature is concerned, the in-medium partial decay widths of the abovementioned process have not been evaluated so far. However, using the quark model authors have predicted the vacuum value of partial decay widths of P-wave scalar $D_0(2400)$ mesons as 248 and 277 MeV, in Refs. [88,89], respectively. Furthermore, in Ref. [87], Lu *et al.* used the $^3P_0$ model to calculate the partial decay width of the $D_s(2317)$ meson through the η-π^0 mixing to be 32 keV in vacuum. Further, by taking D_{s0} as the four-quark state, Nielsen *et al.* observed its partial decay width to $D_s\pi$ to be 6 keV [90]. Also, in Ref. [91] the abovementioned width was observed to be 21.5 keV, using full chiral theory upon equating the mass gap of 0^+ and 1^+ states with 0^- and 1^- states. Moreover, by considering the D_{s0} state to be $s_l^P = 1/2^+$ and using heavy quark symmetries along with the vector meson dominance ansatz, Bardeen *et al.* observed the value of $\Gamma_{D_s\pi}(D_{s0}) \simeq$ 7 keV [92]. Similar results of partial decay widths of the abovementioned process were observed to be 10, 16, and 39 keV in Refs. [93–95], respectively.

It should be noted that the values of the above-discussed partial decay widths of D_0 and D_{s0} mesons are quite model dependent. For example, in Ref. [96] (Ref. [90]), the authors considered D_0 (D_{s0}) states to be diquark-antidiquark states and used the QCD sum rule analysis to find the vacuum values of $\Gamma_{D\pi}(D_0)$ $[\Gamma_{D_s\pi}(D_{s0})]$ through the equation

$$\Gamma(D_0 \rightarrow D\pi) = \frac{1}{16\pi m_{D_0}^3} g_{D_0D\pi}^2 \sqrt{\lambda\left(m_{D_0}^2, m_D^2, m_\pi^2\right)}, \quad (35)$$

where $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$. Here $g_{D_{s0}D_s\pi}$ is the coupling constant of the respective mesons. Further in Eq. (35), for the decay width of the process $D_{s0} \rightarrow D_s + \pi$, the values of m_{D_0}, m_D, and $g_{D_0D\pi}$ are replaced by $m_{D_{s0}}$, m_{D_s}, and $g_{D_{s0}D_s\pi}$, respectively. Also, the values of coupling constants $g_{D_0D\pi}$ and $g_{D_{s0}D_s\pi}$ are given as 6.94 and 0.050 GeV, respectively [90,96]. By using this analysis authors found the vacuum values of $\Gamma_{D\pi}(D_0)$ and $\Gamma_{D_s\pi}(D_{s0})$ to be 120 and 0.006 MeV, respectively. Furthermore, we try to incorporate the medium effects on $\Gamma_{D\pi}(D_0)$ and $\Gamma_{D_s\pi}(D_{s0})$ by using the in-medium masses of the respective mesons in Eq. (35). While doing so we observe that in symmetric nuclear medium and at baryonic density ρ_0, the value of $\Gamma_{D\pi}(D_0)$ $[\Gamma_{D_s\pi}(D_{s0})]$ is enhanced to 40% (25%). On the other hand, the values of $\Gamma_{D\pi}(D_0)$ $[\Gamma_{D_s\pi}(D_{s0})]$ calculated in the present work increase to 20.8% (45%), if we shift from vacuum to nuclear medium ($\rho_B = \rho_0$ and $T = 0$).

VI. SUMMARY

We observed the positive (negative) shifts in masses (decay constants) of scalar $D_0(2400)$ and $D_{s0}(2317)$ mesons using the chiral SU(3) model and QCD sum rules. Using the chiral SU(3) model along with mean-field approximation, we observe the effect of the finite temperature T, the baryonic density ρ_B, the strangeness fraction f_s, and the isospin asymmetric parameter I on the light quark and gluon condensates. Further, we take the abovementioned condensates as inputs in the QCD sum rule calculations to investigate the in-medium masses and decay constants of D_0 and D_{s0} mesons. We observe that a finite baryonic density of the medium causes an increase (decrease) in the values of the masses (decay constants) of D_0 and D_{s0} mesons. However, a finite temperature of the medium causes a decrease (increase), whereas a finite strangeness fraction causes an increase (decrease) in the values of the masses (decay constants) of D_0 and D_{s0} mesons. Further, as a function of the isospin asymmetry of the medium, the values of the masses (decay constants) decrease (increase) for D_0^0 mesons, whereas for D_0^+ mesons these values increase (decrease). Furthermore, we take the in-medium masses of these scalar D_0 and D_{s0} mesons as an application in the $^3P_0$ model and evaluate their in-medium partial decay widths for the processes $D_0(2400) \rightarrow D + \pi$ and $D_{s0}(2317) \rightarrow D_s + \pi$. We observe that as the masses of scalar D_0 and D_{s0} mesons increase in the hyperonic (along with the nucleons) medium, this results in significant increases in the corresponding partial decay widths. The above results may be verified from future heavy-ion collision experiments like CBM and PANDA at GSI, Germany.

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