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

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Abstract

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 chiral SU(3) model. In-medium light quark condensates, $\langle \bar{u}u \rangle_{\rho_B}$ and $\langle \bar{d}d \rangle_{\rho_B}$, the strange quark condensates, $\langle \bar{s}s \rangle_{\rho_B}$, and the gluon condensates, $\langle \frac{2}{3} G_{\mu\nu} G^{\mu\nu} \rangle_{\rho_B}$, needed in QCD sum rule calculations are evaluated using chiral SU(3) model. As an application, we calculate the in-medium partial decay width of scalar $D_0$ ($D_{s0}$) meson decaying to $D + \pi$ ($D_s + \pi$) pseudoscalar mesons using $^3P_0$ 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 the future experiments like CBM and PANDA under the FAIR facility where the study of charmed hadrons is one of major goal.

Keywords: Dense hadronic matter, strangeness fraction, heavy-ion collisions, effective chiral model, QCD sum rules, heavy mesons.

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I. INTRODUCTION

In-medium study of $D$ meson has been an object of intense study [1–13], because of the observation of its enhanced yield [14–16] and also its possible consequence on the yield of higher charmonium states observed in heavy-ion collision (HIC) experiments [17–20]. Firstly, it was proposed by Matsui and Satz that the decrease in the yield of $J/\psi$ state in HICs due to color screening effect should be considered as a probe of the production of the state existed in early universe, i.e., Quark Gluon Plasma (QGP) [21]. Since then, imperative results in the favour of $J/\psi$ suppression were observed at CERN SPS and in the RHIC experiment [17–20]. The statistical recombination of primordially produced charm quark pairs may lead to the increase in the yield of $J/\psi$ mesons and this picture is more important at LHC energies [22, 23]. The behaviour of in-medium masses and spectral width of $D$ mesons will play an important role on the final yield of charmonium. If the drop in the mass of $D$ meson in medium is large enough then the higher charmonium states may decay to $D\bar{D}$ pairs instead of $J/\psi$ states and this will further support the suppression of $J/\psi$ in HIC experiments. The drop in the mass of $D$ mesons in the medium will also decrease the threshold energy required for dissociation process like $J/\psi + \pi \rightarrow D + \bar{D}$ and will effect the absorption cross-section [24, 25]. On the contrary, if the mass of $D$ meson increase in the medium, as was observed in PNJL model calculations, then these mesons may act as facilitators to the production of $J/\psi$ state in the HIC experiments [26].

Moreover, the study of $D$ mesons in nuclear as well as in strange hadronic matter might enlight the formation of bound state of $D$ meson with nucleons [5] as well as with hyperons [6]. Further, the calculation of in-medium ratios of decay constants, $\frac{f_{D_{s0}}}{f_{D_0}}$, of charmed scalar mesons may also be used to measure the extent of flavour symmetry breaking in the strange hadronic matter as is done for pseudoscalar D mesons, $\frac{f_{D_s}}{f_D}$ [27–29]. Upcoming experiment of Facility for Antiproton and Ion Research (FAIR) project at GSI, Germany will provide an 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) will focus on the charmed spectroscopy and on in-medium decay widths of the charmed hadrons. CBM experiment may explore the phase of high baryonic density and moderate temperature which is just complement to the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC). Apart from this, open charmed mesons are ex-
pected to be produced in the J-PARC facility which motivate us to study the properties of $D$ mesons in nuclear as well as in strange hadronic matter $^{30,31}$. The study of in-medium behavior of $D$ mesons may help to understand the experimentally observed elliptic flow, $v_2$, and nuclear modification factor, $R_{AA}$, of these meson, as described in recent review $^{32}$.

On the phenomenological side, many methodologies have been developed to study the in-medium properties of $D$ mesons. For example, Quark Meson Coupling Model (QMC) had predicted a negative shift in the mass of $D$ meson $^5$. The self-consistent coupled channel approach predicted a positive and negative shift in the mass for pseudoscalar $D$ $^9$ and $D_s$ meson $^{10}$, respectively. This model was also used to investigate the scalar charm resonances of $D_{s0}(2317)$ and $D_{0}(2400)$ mesons $^{33}$ and observed the large medium effects for $D_{s0}(2317)$ meson as compared to $D_{0}(2400)$ meson. Here the QMC model treat 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, self consistent coupled channel approach considers the hadrons as degrees of freedom $^8$, and this undergo necessary modifications e.g., from SU(3) flavour $^8$, to SU(4) and breaking of SU(4) symmetry via exchange of vector mesons $^6,34$.

Another approach is QCD sum rules, in which the operator product expansion (OPE) is applied on the current-current correlation function $^{35}$. In this analysis, using the Borel transformation the mass dependent terms are related with the quark as well as 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 leading order term $^{36}$ and up to next to leading order term $^{13}$. In this technique the quark and gluon condensates needed for the QCD sum rules analysis were calculated using linear density approximation. The chiral SU(3) model generalized to SU(4) sector, had also been used to investigate the shift in the masses of $D$ mesons $^4,12,37,38$. In $^7$, the chiral SU(3) model in-conjunction with QCD sum rules was applied successfully to study the in-medium masses of scalar mesons in nuclear medium. The in-medium properties of pseudoscalar, vector and axial vector $D$ meson were investigated in $^{39,40}$. In the present work, we will evaluate the shift in the masses and decay constants of scalar $D_0$ and $D_{s0}$ mesons in asymmetric strange hadronic medium at finite temperatures. The in-medium properties of scalar $D_{s0}$ mesons were not addressed in $^7$ and owing to the presence of strange quark, the behaviour of these mesons in strange matter will of be considerable interest.
Furthermore, as an application of our work we shall investigate the in-medium partial decay width of \( D_0 \) and \( D_{s0} \) for process \( D_0 \to D + \pi \) (\( D_{s0} \to D_s + \pi \)). To achieve this goal, we use \(^3P_0\) model [41], which has been widely used in the past to evaluate the two body decay of the various mesons [41–53]. The medium effects will be introduced through the medium modified mass of these mesons. Here, we use the in-medium mass of pseudoscalar \( D \) meson as calculated in our previous work using chiral SU(3) model and QCD sum rule approach [40]. Additionally we take the in-medium pion mass as calculated using the in-medium chiral perturbative theory [54].

This article is organized as follows: In section 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 is discussed in section III while the \(^3P_0\) model used to evaluate in-medium partial decay width of \( D_0(D_{s0}) \) mesons is narrated in section IV. In section V, we present the various results of the present work and finally in section VI we shall 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 \( \langle \alpha_s G^{a}_{\mu\nu} G^{a}_{\mu\nu} \rangle_{\rho_B} \). Chiral SU(3) model contains an effective Lagrangian density, which include kinetic energy term, baryon meson interaction term which produce baryon mass, self-interaction of vector mesons which generates the dynamical mass of vector mesons, scalar mesons interactions which induce the spontaneous breaking of chiral symmetry, and the explicit breaking term of chiral symmetry. In the strange hadronic medium, in-medium baryon masses are modified in chiral SU(3) model through the exchange of scalar iso-scalar mesons \( \sigma \) and \( \zeta \) and scalar iso-vector field \( \delta \). Within mean field approximation, from the effective Lagrangian density of the model, using Euler Lagrange equation \( \frac{\partial L}{\partial \phi} - \partial_\mu \left( \frac{\partial L}{\partial (\partial_\mu \phi)} \right) = 0 \), where \( \phi \) is scalar field, we obtain equations of motion for \( \sigma, \zeta, \delta \) and scalar dilaton field \( \chi \). These are given as [55, 56]

\[
\begin{align*}
    &k_0 \chi^2 \sigma - 4k_1 \left( \sigma^2 + \zeta^2 + \delta^2 \right) \sigma - 2k_2 \left( \sigma^3 + 3\sigma \delta^2 \right) - 2k_3 \chi \sigma \zeta \\
    &- \frac{d}{3} \chi^4 \left( \frac{2\sigma}{\sigma^2 - \delta^2} \right) + \left( \frac{\chi}{\chi_0} \right)^2 m^2_{\pi} f_\pi - \sum g_{\sigma i} p_i^s = 0,
\end{align*}
\]  

(1)
\[
\begin{align*}
&k_0 \chi^2 \zeta - 4k_1 (\sigma^2 + \zeta^2 + \delta^2) \zeta - 4k_2 \chi (\sigma^2 - \delta^2) \\
&\quad - \frac{d \chi^4}{3 \zeta} + \left( \frac{\chi}{\chi_0} \right)^2 \left[ \sqrt{2m_K^2 f_K} - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right] - \sum g_{\zeta i} \rho_i^s = 0, \\
&k_0 \chi^2 \delta - 4k_1 (\sigma^2 + \zeta^2 + \delta^2) \delta - 2k_2 (\delta^3 + 3\sigma^2 \delta) + k_3 \chi \delta \chi
\end{align*}
\]

(2)

\[
\begin{align*}
&\frac{2}{3} \frac{d\chi^4}{\sigma^2 - \delta^2} - \sum g_{\delta i} \rho_i^s = 0, \\
&k_0 \chi (\sigma^2 + \zeta^2 + \delta^2) - k_3 (\sigma^2 - \delta^2) \zeta + \chi^3 \left[ 1 + \ln \left( \frac{\chi^4}{\chi_0^4} \right) \right] + (4k_4 - d) \chi^3 \\
&\quad - \frac{4}{3} d\chi^3 \ln \left( \left( \frac{(\sigma^2 - \delta^2) \zeta}{\sigma_0^2 \zeta_0} \right) \left( \frac{\chi}{\chi_0} \right)^3 \right) \\
&\quad + \frac{2\chi}{\chi_0^2} \left[ m_\pi^2 f_\pi \sigma + \left( \sqrt{2m_K^2 f_K} - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta \right] = 0,
\end{align*}
\]

(3)

respectively. In above, \(m_\pi, m_K\) and \(f_\pi, f_K\) denote the mass and decay constant of \(\pi, K\) mesons, respectively, and the other parameters \(k_0, k_1, k_2, k_3\) and \(k_4\) are fitted so as to reproduce the vacuum masses of \(\eta, \eta'\) mesons \[57\]. Further, \(\rho_i^s\) represents the scalar density for \(i\)th baryon \((i = p, n, L, \Sigma^{\pm, 0}, \Xi^{-, 0})\) and is defined as

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

\[(5)\]

where, \(E_i^s(k) = (k^2 + m_i^s)^{1/2}\) 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 baryon of species \(i\), and \(\gamma_i = 2\) is the spin degeneracy factor. Also, \(m_i^s = -g_{\sigma i} \sigma - g_{\zeta i} \zeta - g_{\delta i} \delta\) 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 \[57\]. In eq. \[4\] \(\sigma_0, \chi_0\) and \(\zeta_0\) denote the vacuum values of the scalar fields \(\sigma, \chi\) and \(\zeta\), respectively.

Furthermore, we solve these equations to find the effect of baryonic density \(\rho_B\), temperature \(T\), finite strangeness fraction \(f_s = \frac{\sum\rho_i^s \rho_i}{\rho_B}\) and isospin asymmetric parameter \(I = \frac{-\sum I_3^s \rho_i}{2\rho_B}\) on \(\sigma, \zeta, \delta\) and \(\chi\) fields. Here, it is to be noted that, \(I_3^s\) is the \(z\)-component of the isospin for the \(i\)th baryon, \(s_i\) is the number of strange quarks and \(\rho_i\) is the number density of \(i\)th baryon.

In the chiral SU(3) model, the explicit symmetry breaking term is used to relate the light and strange quark condensates with \(\sigma, \zeta, \delta\) and \(\chi\) fields as follows \[55\],

\[\text{(5)}\]
\[ \langle \bar{u}u \rangle = \frac{1}{m_u} \left( \frac{\chi}{\chi_0} \right)^2 \left[ \frac{1}{2} m_{\pi}^2 f_{\pi} (\sigma + \delta) \right], \tag{6} \]

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

and

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

respectively.

Furthermore, using the trace anomaly property of QCD we extract the gluon condensates in terms of the above mentioned scalar fields using \[56, 57\]

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

In the above equation, \(d\) denotes a constant with a value of \((2/11)\), and it is evaluated using one loop beta function for the three flavors and colors of QCD \[57\].

### III. QCD SUM RULE FOR \(D_0\) AND \(D_{s0}\) MESONS

We will 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 start with two point correlation function

\[ \Pi(q) = i \int d^4x \ e^{iq.x} \langle \mathcal{T} \{J(x)J^\dagger(0)\} \rangle_{\rho B, T}, \tag{10} \]

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

\[ J(x) = J^\dagger(x) = \frac{\bar{c}(x)q(x) + \bar{q}(x)c(x)}{2}. \tag{11} \]

Note that in above, we consider the averaged scalar currents of particle \(D_0\) and its antiparticle \(\bar{D}_0\) mesons and thus, we will evaluate the averaged shift in masses and decay constants of scalar \(D_0\) and similarly, for \(D_{s0}\) mesons \[35, 58, 59\]. As mentioned earlier, we will evaluate the properties of \(D_0\) and \(D_{s0}\) meson 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 isospin doublet of scalar $D_0$ mesons. In eq. 11, for $D_0^+$ and $D_0^0$ mesons quark field $q(x)$ will be replaced by $d(x)$ and $u(x)$, respectively, whereas for $D_{s0}$ mesons $q(x)$ will be replaced by $s(x)$. The mass splitting between particle-antiparticles can be evaluated by separating the two point correlation function into even and odd part as was done in [60]. In the rest frame of nucleons, following the Fermi gas approximation, we divide the two point correlation function into vacuum part, nucleon and temperature dependent part, i.e.,

$$ \Pi(q) = \Pi_0(q) + \frac{\rho_B}{2m_N} T_N(q) + \Pi_{P.B.}(q, T), \quad (12) $$

where $T_N(q)$ is the forward scattering amplitude, $\rho_B$ and $m_N$ denote the total baryon density and nucleon mass, respectively. The third term represents the thermal correlation function and is defined as [61]

$$ \Pi_{P.B.}(q, T) = i \int d^4x \ e^{i q \cdot x} \langle T \{ J(x) J^\dagger(0) \} \rangle_T, \quad (13) $$

where $\langle T \{ J_5(x) J_5^\dagger(0) \} \rangle_T$ is the thermal average of the time ordered product of the scalar currents. Further, thermal average of any operator $O$ is given by [61]

$$ \langle O \rangle_T = \frac{Tr \{ \exp (-H/T) O \}}{Tr \{ \exp (-H/T) \}}, \quad (14) $$

In above $Tr$ denotes the trace over complete set of states and $H$ is the QCD Hamiltonian. The factor $\frac{\exp(-H/T)}{Tr\{\exp(-H/T)\}}$ is the thermal density matrix of QCD. In eq. 12, the third term corresponds to the pion bath term and had been widely used in the past to consider the effect of temperature of the medium [62, 63]. 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 scalar fields $\sigma$, $\zeta$, $\delta$ and $\chi$ in terms of which scalar quark and gluon condensates are expressed and therefore, we neglect the third term in eq. (12).

The scattering amplitude $T_N(q)$, near the pole position of the scalar meson is represented in terms of the spectral density [58], which in the limit of $q \to 0$, is parametrized in terms of three unknown parameters $a$, $b$ and $c$, given as [1, 13, 59],

$$ \rho(\omega, 0) = -\frac{f_{D_0/D_{s0}}^2 m_{D_0/D_{s0}}^4}{\pi m_c^2} \text{Im} \left[ \frac{T_{D_0/D_{s0}}(\omega, 0)}{(\omega^2 - m_{D_0/D_{s0}}^2 + i\varepsilon)^2} \right] + \cdots $$
\[ a \frac{d}{d\omega^2} \delta(\omega^2 - m^2_{D_0/D_{s0}}) + b \delta(\omega^2 - m^2_{D_0/D_{s0}}) + c \theta(\omega^2 - s_0). \] (15)

Here, \( m_{D_0/D_{s0}} \) and \( f_{D_0/D_{s0}} \) are the masses and decay constants of \( D_0/D_{s0} \) mesons and \( m_c \) denotes the mass of charm quark. Also the first term in eq. (15) denotes the double pole term and exhibit the on shell effect of the \( T \)-matrix, whereas the second term represents single pole term which exhibit 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 [36]. Finally, the shift in masses and decay constants of \( D_0/D_{s0} \) mesons from their vacuum value is given as [7, 36]

\[ \delta m_{D_0/D_{s0}} = 2\pi \frac{m_N + m_{D_0/D_{s0}}}{m_N m_{D_0/D_{s0}}} \rho_B a_{D_0/D_{s0}}, \] (16)

and

\[ \delta f_{D_0/D_{s0}} = \frac{m_c^2}{2f_{D_0/D_{s0}} m_N} \left( \frac{b \rho_B}{2m_N} - \frac{4 f^2_{D_0/D_{s0}} m^3_{D_0/D_{s0}}}{m^2_{D_0/D_{s0}}} \frac{\delta m_{D_0/D_{s0}}}{m^2_c} \right), \] (17)

respectively. Clearly, in order to calculate the shift in mass and decay constant of \( D_0/D_{s0} \) mesons we shall need to find the values of unknown parameters \( a \) and \( b \). To achieve this task, we apply the Borel transformation on the forward scattering amplitude \( T_N(\omega, 0) \) on hadronic side as well as on the forward scattering amplitude \( T_N(\omega, 0) \) on operator product expansion (OPE) side in the rest frame of the nuclear matter. After this, we equate these two equations and this lead to [7, 36]
\[ a \left\{ \frac{1}{M^2} \exp \left( -\frac{m_{D_0/D_{s0}}^2}{M^2} \right) - \frac{s_0}{m_{D_0/D_{s0}}^2} \exp \left( -\frac{s_0}{M^2} \right) \right\} + b \left\{ \exp \left( -\frac{m_{D_0/D_{s0}}^2}{M^2} \right) - \frac{s_0}{m_{D_0/D_{s0}}^2} \exp \left( -\frac{s_0}{M^2} \right) \right\} + \frac{2m_N(m_H - m_N)}{(m_H - m_N)^2 - m_{D_0/D_{s0}}^2} \left( \frac{f_{D_0/D_{s0}}m_{D_0/D_{s0}}g_{D_0/D_{s0}}N_H}{m_c} \right)^2 \times \left\{ \frac{1}{(m_H - m_N)^2 - m_{D_0/D_{s0}}^2} - \frac{1}{M^2} \right\} \exp \left( -\frac{m_{D_0/D_{s0}}^2}{M^2} \right) \right\} \\
= + \frac{m_c\langle \bar{q}q \rangle_N}{2} \times \exp \left( -\frac{m_{c/b}}{M^2} \right) + \frac{1}{2} \left\{ -2 \left( 1 - \frac{m_c^2}{M^2} \right) \langle q^+iD_0q \rangle_N + \frac{4m_c}{M^2} \left( 1 - \frac{m_c^2}{2M^2} \right) \langle \bar{q}iD_0iD_0q \rangle_N + \frac{1}{12} \frac{\langle \alpha_s G\pi \rangle_N}{\pi} \right\} \times \exp \left( -\frac{m_c^2}{M^2} \right). \] (18)

Here, to find the values of two unknown parameters \(a\) and \(b\) we differentiate above equation w.r.t. \(\frac{1}{M^2}\) to find another equation and then solve these two equations. The nucleon expectation value of the various condensates appearing in eq. (18) is written as

\[ \mathcal{O}_N = [\mathcal{O}_{\rho B} - \mathcal{O}_{\text{vacuum}}] \frac{2m_N}{\rho_B}. \] (19)

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

\[ \langle u\bar{u} \rangle_N = [\langle u\bar{u} \rangle_{\rho B} - \langle u\bar{u} \rangle_{\text{vacuum}}] \frac{2m_N}{\rho_B}, \] (20)

\[ \langle d\bar{d} \rangle_N = [\langle d\bar{d} \rangle_{\rho B} - \langle d\bar{d} \rangle_{\text{vacuum}}] \frac{2m_N}{\rho_B}, \] (21)

and

\[ \left\langle \frac{\alpha_s}{\pi} G^{a\mu\nu}G^{a\mu\nu} \right\rangle_N = \left[ \left\langle \frac{\alpha_s}{\pi} G^{a\mu\nu}G^{a\mu\nu} \right\rangle_{\rho B} - \left\langle \frac{\alpha_s}{\pi} G^{a\mu\nu}G^{a\mu\nu} \right\rangle_{\text{vacuum}} \right] \frac{2m_N}{\rho_B}. \] (22)

The condensates \(\langle \bar{q}gs\sigma Gq \rangle_{\rho B}\) and \(\langle \bar{q}iD_0iD_0q \rangle_{\rho B}\) appearing in Borel transformed QCD sum rule equation are expressed in terms of light quark condensates and we write

\[ \langle \bar{q}gs\sigma Gq \rangle_{\rho B} = \lambda^2 \langle \bar{q}q \rangle_{\rho B} + 3.0 GeV^2 \rho_B. \] (23)
and

\[ \langle ar{q} i D_0 i D_0 q \rangle_{\rho_B} + \frac{1}{8} \langle \bar{q} g_s \sigma G q \rangle_{\rho_B} = 0.3 \text{GeV}^2 \rho_B. \]  

(24)

The condensate \( \langle q^4 i D_0 q \rangle_N \) is not calculated in the chiral SU(3) model and we consider its value as calculated in linear density approximation for our calculations. We will use the values 0.18 GeV\(^2\) \( \rho_B \) and 0.018 GeV\(^2\) \( \rho_B \) for \( \langle u^4 i D_0 u \rangle_N \) and \( \langle s^4 i D_0 s \rangle_N \), respectively. However, later on we will see that \( \langle q^4 i D_0 q \rangle_N \) does not affect significantly the in-medium properties of \( D_0 \) and \( D_{s0} \) mesons.

IV. \( 3^P_0 \) MODEL

To calculate the in-medium partial decay width of \( D_0 \to D + \pi \) (\( D_{s0} \to D_s + \pi \)), we use \( 3^P_0 \) model, in which quark and anti-quark pair is created in vacuum (0\(^++\)) \[41, 42\]. This model had been used in literature to find the strong decays of hidden charmed states \[43, 44\], open charmed bottom states \[45, 46\] as well as of bottom mesons \[46, 49\]. In the present work of finding the two body decay of \( D_0/D_{s0} \) mesons, we use the transition operator as taken in \[65\], and find the helicity amplitude given by \[66\]

\[
\mathcal{M}^{M_{D_0} M_{D} M_{\pi}} = \gamma \sqrt{8 E_{D_0} E_{D} E_{\pi}} \sum_{M_{L_{D_0}}, M_{L_{D}}, M_{S_{D_0}}, M_{S_{D}}, M_{L_{\pi}}, M_{S_{\pi}}, m} \langle 1m; 1 - m | 00 \rangle \\
\times \langle L_{D_0} M_{L_{D_0}} S_{D_0} M_{S_{D_0}} | J_{D_0} M_{J_{D_0}} \rangle \langle L_{D} M_{L_{D}} S_{D} M_{S_{D}} | J_{D} M_{J_{D}} \rangle \langle L_{\pi} M_{L_{\pi}} S_{\pi} M_{S_{\pi}} | J_{\pi} M_{J_{\pi}} \rangle \\
\times \langle \varphi_{D}^{12} \varphi_{\pi}^{24} | \varphi_{D_0}^{12} \varphi_{0}^{24} \rangle \langle \chi_{S_{D} M_{S_{D}}}^{13} \chi_{S_{\pi} M_{S_{\pi}}}^{24} | \chi_{S_{D_0} M_{S_{D_0}}}^{12} \chi_{S_{\pi} M_{S_{\pi}}}^{34} \rangle I_{M_{L_{D}}, M_{L_{\pi}}, M_{\pi}}^{M_{L_{D_0}}, M_{L_{D}}, M_{S_{D_0}}, M_{S_{D}}, M_{L_{\pi}}, M_{S_{\pi}}, m}(k). \]  

(25)

In above, \( E_{D_0} = m_{D_0}^* \), \( E_D = \sqrt{m_D^* + K_D^2} \) and \( E_\pi = \sqrt{m_\pi^* + K_\pi^2} \) represent the energies of respective mesons. Here \( m_{D_0}^* \), \( m_D^* \) and \( m_\pi^* \) are the in-medium masses of \( D_0 \), \( D \) and \( \pi \) mesons, respectively. We then calculate the spin matrix elements \( \langle \chi_{S_{D} M_{S_{D}}}^{13} \chi_{S_{\pi} M_{S_{\pi}}}^{24} | \chi_{S_{D_0} M_{S_{D_0}}}^{12} \chi_{S_{\pi} M_{S_{\pi}}}^{34} \rangle \) in terms of the Wigner’s 9j symbol, and the flavor matrix element \( \langle \varphi_{D}^{12} \varphi_{\pi}^{24} | \varphi_{D_0}^{12} \varphi_{0}^{24} \rangle \) in terms of isospin of quarks as done in Refs. \[42, 65, 66\]. In eq. (25), \( I_{M_{L_{D}}, M_{L_{\pi}}, M_{\pi}}^{M_{L_{D_0}}, M_{L_{D}}, M_{S_{D_0}}, M_{S_{D}}, M_{L_{\pi}}, M_{S_{\pi}}, m}(k) \) 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

\[
\psi_{nLM_{L}} = (-1)^n (-\ell)^L R^{L + \frac{1}{2}} \sqrt{\frac{2m!}{\Gamma(n + L + \frac{1}{2})}} \exp \left( -\frac{R^2 k^2}{2} \right) L^{L + \frac{1}{2}} (R^2 k^2) Y_{lm}(k). \]

(26)
Here, $R$ is the radius of the meson, $L_n^{L+\frac{1}{2}}(R^2k^2)$ represents associate Laguerre polynomial and $Y_{lm}(k)$ denotes the spherical harmonic function.

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

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

where,

$$
I_0 = -4\frac{\sqrt{3}}{\pi^{5/4}} \frac{R_{D_0}^{5/2}R_D^{3/2}R_\pi^{3/2}}{(R_{D_0}^2 + R_D^2 + R_\pi^2)^{5/2}} \left\{ 1 - k_D^2 \frac{(2R_{D_0}^2 + R_D^2 + R_\pi^2)(R_D^2 + R_\pi^2)}{4(R_{D_0}^2 + R_D^2 + R_\pi^2)} \right\}
\times \exp \left[ -\frac{k_D^2 R_{D_0}^2(R_D^2 + R_\pi^2)}{8(R_{D_0}^2 + R_D^2 + R_\pi^2)} \right],
$$

and

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

We then finally calculate the decay width, using

$$
\Gamma = \pi^2 \frac{|k_D|^2}{m_A^2} \sum_{JL} |\mathcal{M}^{JL}|^2,
$$

where, $\gamma$ is the strength of the pair creation in the vacuum and its value is taken as 6.74 \cite{66}. Also, $|k_D|$ represents the momentum of the $D$ and $\pi$ mesons in the rest mass frame of $D_0$ meson and is given by,

$$
|k_D| = \frac{\sqrt{[m_{D_0}^2 - (m_D^* - m_\pi^*)^2][m_{D_0}^* - (m_D^* + m_\pi^*)^2]}}{2m_{D_0}^*}.
$$

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

V. RESULTS AND DISCUSSION

This section will elaborate the results of the present investigation. We use, nuclear saturation density, $\rho_0 = 0.15$ fm$^{-3}$, the average values of coupling constants for scalar $D_0/D_{s0}$ mesons $g_{D_0/D_{s0}N\Lambda}$ $\approx 6.74$, the values of continuum threshold parameter $s_0$,
for $D^+_0$, $D^0_0$ and $D_{s0}$ mesons as 8, 8 and 7 GeV$^2$, respectively. 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 shall represent the shift in masses and decay constants of $D^+_0$, $D^0_0$ and $D_{s0}$ mesons as a function of 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 as (5-9) GeV$^2$.

A. Shift in masses and decay constants

In fig. 1 (fig. 2) we represent the shift in masses (decay constants) of isospin doublet of scalar $D_0$ mesons, whereas in fig. 3 we plot the shift in masses and decay constants of

| $f_s$ | $I=0$ | $I=0.5$ |
|------|-------|---------|
|      | $T=0$ | $T=100$ MeV | $T=0$ | $T=100$ MeV |
|      | $\rho_0$ | $4\rho_0$ | $\rho_0$ | $4\rho_0$ | $\rho_0$ | $4\rho_0$ |
| $\delta m_{D^0_0}$ | 0 | 87 | 162 | 76 | 156 | 78 | 148 | 72 | 143 |
|     | 0.5 | 103 | 171 | 93 | 162 | 87 | 150 | 80 | 145 |
| $\delta m_{D^+_0}$ | 0 | 64 | 125 | 58 | 120 | 68 | 127 | 62 | 123 |
|     | 0.5 | 76 | 129 | 69 | 123 | 84 | 139 | 79 | 145 |
| $\delta m_{D_{s0}}$ | 0 | 81 | 158 | 67 | 140 | 73 | 140 | 66 | 137 |
|     | 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 |
|     | 0.5 | -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 |
|     | 0.5 | -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 |
|     | 0.5 | -11 | -21 | -9.6 | -19 | -11.5 | -22.7 | -10 | -20.4 |

TABLE I: In above, we tabulate the values of shift in masses and decay constants of $D^0_0$, $D^+_0$ and $D_{s0}$ mesons (in units of MeV).
$D_{s0}$ mesons in isospin asymmetric hot and dense strange hadronic medium as a function of squared Borel mass parameter, $M^2$. In table I we give the numerical values of shift in masses and decay constants of these mesons. Here, in the present investigation, we notice an enhancement in the masses, whereas drop in the values of decay constants of scalar $D_0$ and $D_{s0}$ mesons in nuclear as well as in the strange hadronic matter. Moreover, for any given value of isospin asymmetric parameter $I$, strangeness fraction $f_s$ and 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, increase as a function of 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.

Similar behaviour we observe for the shift in masses and decay constants of above mentioned mesons at finite strangeness fraction $f_s$. For example, in symmetric strange hadronic medium, $f_s=0.5$, the values of the masses (decay constants) of $D_0^0$, $D_0^+$ and $D_{s0}$ mesons increase (decrease) by 4% (3.2%), 3% (2.6%) and 4.8% (3.3%), respectively from their vacuum values, at $\rho_B = \rho_0$ and temperature $T=0$. Likewise, at baryonic density $4\rho_0$, these percentage values further enhance to 7% (5.9%), 5.3%(4.4%) and 10%(6.3%), respectively. Further, we notice that the shift in masses and decay constants of $D_{s0}$ mesons is more sensitive to the finite strangeness fraction in the medium as compared to the non-strange $D_0$ mesons. This can be understood on the basis that the in-medium mass and decay shift of $D_0$ mesons depend upon the light quark condensate $\langle \bar{q}q \rangle$, whereas that of $D_{s0}$ mesons is evaluated using strange quark condensates $\langle \bar{s}s \rangle$. As can be seen from eq. (8), the strange quark condensate $\langle \bar{s}s \rangle$ is proportional to the strange scalar field $\zeta$ which is more sensitive to the strangeness fraction of the medium as compared to non-strange scalar field $\sigma$.

The effect of finite temperature on the mass and decay shift of above mentioned mesons is observed to be opposite to that of strangeness fraction. For example, at finite temperature medium i.e., $T = 100$ MeV, we observe the percentage of increase (drop) in the masses (decay constants) of $D_0^0$, $D_0^+$ and $D_{s0}$ mesons as 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
FIG. 1: Figure shows the variation of shift in masses of scalar $D_0^0$ and $D_0^{+}$ mesons as a function of squared Borel mass parameter, $M^2$ for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV and strangeness fractions $f_s = 0$ and 0.5. The results are given at baryonic densities $\rho_0$ and $4\rho_0$.

the same medium but at zero temperature. Therefore, finite temperature of the medium cause decrease in the masses, whereas increase in the values of decay constants of $D_0^0$, $D_0^{+}$ and $D_{s0}$ mesons.

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 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, $4\rho_0$, above percentage values shift to 0.5% (0.2%) and 0.6% (0.09%), respectively. The change in isospin asymmetry of the medium also effect the in-medium masses of scalar $D_{s0}$ mesons. For example, at baryonic density $\rho_0$ on shifting
FIG. 2: Figure shows the variation of shift in decay constants of scalar $D_0^0$ and $D_0^+$ mesons as a function of squared Borel mass parameter, $M^2$ for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV and strangeness fractions $f_s = 0$ and 0.5. The results are given at baryonic densities $\rho_0$ and $4\rho_0$.

From $I = 0$ to 0.5, we observed 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 enhance to 0.7% (0.47%), at higher baryonic density $4\rho_0$.

In [40], we observed negative shift in the masses of pseudo-scalar $D$ meson using chiral SU(3) model and QCD sum rules. The opposite shift in the mass of scalar $D_0$ and pseudo-scalar $D$ meson is due to the opposite sign with the term $m_c\langle\bar{q}q\rangle N^2$ eq. (18), present in the Borel transformed equation (also see eq. (19) of [40]). This causes negative and positive value of the unknown parameter $a$ [13], calculated for scalar $D_0^0$ and pseudo-scalar $D$ mesons, respectively. This further cause 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
FIG. 3: Figure shows the variation of shift in mass and decay constant of scalar $D_s^0$ mesons as a function of squared Borel mass parameter, $M^2$ for isospin asymmetric parameters $I = 0$ and 0.5, temperatures $T = 0$ and 100 MeV and strangeness fractions $f_s = 0$ and 0.5. The results are given at baryonic densities $\rho_0$ and $4\rho_0$, corresponding to scattering of $D^0_0$ and $D^0$ mesons with nucleons as a function of 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 flavour symmetry breaking in the medium, in fig. 5 we plot the ratio of in-medium decay constants of $\frac{f_{D^0_0}}{f_{D^+_0}}$ (subplot (a)), $\frac{f_{D^0_0}}{f_{D^+_0}}$ (subplot (b)) and $\frac{f_{D^0_0}}{f_{D^+_0}}$ (subplot (c)) as a function of baryonic density at $T=0$. As expected, the ratio $\frac{f_{D^0_0}}{f_{D^+_0}}$ is more sensitive to the isospin asymmetry of the medium as compared to strangeness fraction. Opposite is true for the in-medium ratios of $\frac{f_{D^0_0}}{f_{D^0}}$ and $\frac{f_{D^0_0}}{f_{D^+_0}}$.

To check the reliability of the results of present work at higher value of baryonic den-
FIG. 4: Figure shows the variation of the scattering length (in fm) of scalar and pseudoscalar $D$ meson with nucleon in nuclear medium.

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 $D_0^+$ ($D_{s0}$) meson (in symmetric nuclear medium) both calculated using the linear density approximation and chiral SU(3) model. Within linear density approximation, the light quark condensate $\langle \bar{d}d \rangle_{\rho_B}$ is calculated using $\langle \bar{d}d \rangle_{\rho_B} = \langle \bar{d}d \rangle_0 + \frac{\sigma_N \rho_B}{m_u + m_d}$, 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 term $\langle \bar{q}q \rangle_0$, is the vacuum value of light quark condensate and is given as (-0.245 GeV)$^3$. Also, the value of $y$ was taken to be 0.5. In addition, we calculate the mass of $D_{0}^{+}$ ($D_{s0}$) meson by considering only condensate $\langle \bar{d}d \rangle_{\rho_B}$ ($\langle \bar{s}s \rangle_{\rho_B}$) in QCD sum rule equations, which we calculate using linear density approximation at zero temperature and 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 chiral SU(3) model, then
FIG. 5: Figure shows the variation of ratio of in-medium decay constants $\frac{f_{D_0^+}}{f_{D_0^+}}$, $\frac{f_{D_s^0}}{f_{D_s^+}}$ and $\frac{f_{D_s^0}}{f_{D_s^0}}$ as a function of baryonic density of the medium.

we observe non-linear decrease as a function of baryonic density of the medium. Similarly, corresponding in-medium mass of $D_0^+$ ($D_{s0}$) meson increase non-linearly as a function of baryonic density. The observed non-linear 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 of the work of [67]. In this work, authors calculated the light quark condensates beyond the linear density approximation using chiral perturbation theory. Therefore, the use of 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 $D_{s0}$ meson at higher baryonic density of the medium using QCD sum rules.

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. (18)) enhances the magnitude of the shift in the mass of above mentioned meson [13]. Further, we notice a major contribution
FIG. 6: Figure shows the variation of in-medium mass of scalar $D_0$, $D_{s0}$ mesons and corresponding light quark, strange quark condensates (calculated using linear density approximation and chiral SU(3) model) as a function of baryonic density of the medium.

of the scalar quark condensates $\langle \bar{q}q \rangle$ to the shift in the mass of scalar $D_0$ and $D_{s0}$ meson as compared to the all other condensates. To understand this, we tabulate the numerical values of shift in the mass of $D_0^+$ and $D_{s0}^0$ meson in tables III and IV respectively. We also notice that the condensate $\langle \bar{q}iD_0q \rangle_N$ which we do not calculate from the chiral SU(3) model has insignificant contribution on the shift in masses of above studied charmed mesons.

The uncertainties in the results of the present calculations may arise because of the medium modification in coupling constant, $g_{D_0/D_{s0}N\Lambda}$ and $g_{D_0/D_{s0}N,\Sigma}$ 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 to decrease the value of coupling constant (continuum threshold parameter) by 5%, then the shift in mass of $D_0^0$ meson decrease (increase) by 1.5%(15%) at baryonic density $\rho_0$, and temperature, $T = 0$. Likewise, the
Table II: In the above table mass shift of $D_0^+$ mesons (in MeV) are compared by considering the contribution of individual condensates.

| Condensates                  | I=0        | I=0.5       |
|------------------------------|------------|-------------|
|                              | T=0  T=100 | T=0  T=100  |
| $\rho_0$                     | 4$\rho_0$  | 4$\rho_0$   |
| All Condensates              | NLO 83 142 | 78 140      |
|                              | LO 64 125  | 58 120      |
| $\langle d\bar{d} \rangle_N \neq 0$ | NLO 84 145 | 78 141      |
|                              | LO 63 132  | 56 126      |
| $\langle \bar{q}i D_{0q} \rangle_N = 0$ | NLO 86 151 | 81 146      |
|                              | LO 66 138  | 59 132      |

Table III: In the above table mass shift of $D_0^0$ mesons (in MeV) are compared by considering the contribution of individual condensates.

| Condensates                  | I=0        | I=0.5       |
|------------------------------|------------|-------------|
|                              | T=0  T=100 | T=0  T=100  |
| $\rho_0$                     | 4$\rho_0$  | 4$\rho_0$   |
| All Condensates              | NLO 103 181| 95 170      |
|                              | LO 87 162  | 76 156      |
| $\langle \bar{u}u \rangle_N \neq 0$ | NLO 105 178| 97 168      |
|                              | LO 85 173  | 75 165      |
| $\langle \bar{q}i D_{0q} \rangle_N = 0$ | NLO 104 184| 92 179      |
|                              | LO 89 180  | 79 173      |

The magnitude of shift in decay constant decrease (decrease) by 0.5%(10%). This indicates that the errors caused by the shift in value of coupling constant (continuum threshold parameter) may have insignificant (significant) effect on the shift in masses and decay constants of $D_0$ and $D_{s0}$ mesons.

Now, we compare the results of the present investigation with the available data of medium modification of scalar $D_0$ mesons. It should be noted that, no work is available in literature within any model which calculate the mass and decay constant of scalar $D_0$ and $D_{s0}$ mesons.
In Ref. [36], author applied linear density QCD sum rule and calculate the positive shift of 69 MeV for $D_0$ meson in cold symmetric nuclear matter. In Ref. [13] by adding the next to leading order term in the QCD sum rules, author found the shift in mass and decay constant of $D_0$ meson as 80 MeV and 11 MeV accordingly at cold and symmetric nuclear matter. Furthermore, an extra widening of large width of the scalar $D_0$ mesons, whereas the width of nearly 100 MeV was observed for the case of $D_{s0}$ meson at normal nuclear matter by using coupled channel approach [3]. In Ref. [2], author observed the mass splitting between $D_0$ and $\bar{D}_0$ meson by dividing the even and odd term of correlation function in nuclear matter. However in the present work as mentioned earlier we observe average mass shift of $D_0$ and $\bar{D}_0$ meson by taking the average particle and antiparticle current. The results of the enhancement in the masses of scalar $D_0/D_{s0}$ meson suggest us that scalar meson may not cause the $J/\psi$ suppression in the HIC experiments and one might think that this enhanced mass of $D_0$ meson may act as facilitators to the production of $J/\psi$ state in heavy ion collision experiments. Also, the positive shift in mass may cause significant change in the values of absorption [25] as well as production cross-section of higher charmonium states observed in HIC experiments [24]. Additionally, this in-medium enhancement may also be reflected through the measured values of the elliptic flow, $v_2$, and nuclear modification factor, $R_{AA}$, of open charmed mesons [68]. Further, the enhanced mass of scalar $D_0$ meson indicate the repulsive interactions of $D_0$ mesons with nucleons as well with the hyperons and therefore, the formation of scalar $D_0$ meson-nucleon/hyperons bound states may not be possible.

B. In-medium partial decay width of $D^0_0(D^+_0)$ and $D_{s0}$ mesons

In this section, using $^3P_0$ model, we shall 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 $\Gamma_{D^+_0 \pi}(D^+_0)$ and $\Gamma_{D^0_0 \pi}(D^0_0)$, whereas in fig. 8 we present $\Gamma_{D_{s0} \pi}(D_{s0})$ as a function of $R_A$ values (where $A$ represents the parent meson). Here, as mentioned earlier, to calculate the in-medium partial decay width for the above mentioned 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 are scalar. For the in-medium mass of pseudoscalar $D$ and $D_s$
FIG. 7: Figure shows the variation of partial decay width of particular decay $D_0^+ \to D^+ + \pi$ and $D_0^0 \to D^0 + \pi$ as a function of $R_A$ value (in GeV$^{-1}$).

mesons, we follow our earlier work [40], where calculation were done using QCD sum rules and chiral SU(3) model. Also, we include the medium modified mass of $\pi$ meson, calculated using chiral perturbation theory [54]. In [54], authors studied the in-medium mass of $\pi$ mesons in symmetric nuclear matter at zero temperature including next to leading order term upto baryonic density $3\rho_0$. As no work is still available on the study of mass shift of $\pi$ mesons in asymmetric strange matter at finite temperatures, therefore 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 fig. 7 and fig. 8, we notice an enhanced in-medium partial decay width for decays $D_0^+ \to D^+ + \pi$, $D_0^0 \to D^0 + \pi$, and $D_{s0} \to D_s + \pi$ as compared to the vacuum values. Moreover, we do not observe any node in the above mentioned partial decay widths since the parent and daughter mesons are
FIG. 8: Figure shows the variation of the partial decay width of a particular decay $D_{s0} \to D_s + \pi$ as a function of respective $R_A$ value (in GeV$^{-1}$).

in their ground states. Also, from eqs. (25), (27) and (30) we note that the value of partial decay width is proportional to the square of decay amplitude, which is further dependent on the spatial integral. Furthermore, this spatial integral has been solved analytically for the respective decay channel (eqs. (28) and (29)) and therefore, behavior of the partial decay width is the resulting effect of the two integrals $I_0$ and $I_1$ occurring in eq. (27). Here through the competitive effect of the two integrals we observe the vacuum values of partial decay widths $\Gamma_{D_s\pi}(D_{s0}^+)$, $\Gamma_{D_s^0\pi}(D_{s0}^0)$ and $\Gamma_{D_s\pi}(D_{s0})$ as 557 and 551 and 374 keV, respectively at $R_A=1.89$ 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, on moving from symmetric nuclear ($f_s = 0$) to strange medium ($f_s = 0.5$), we observe enhancement in the respective values of partial decay width and 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 $D_{s0}$ meson is much sensitive to the finite strangeness fraction and therefore, the increase in the value of $\Gamma_{D_{s0}^0}(D_{s0})$ is more as compared to $\Gamma_{D_{s0}^+}(D_{s0}^0)$ and $\Gamma_{D_{s0}^0}(D_{s0}^0)$ in symmetric strange hadronic matter. On the other hand, on increasing the temperature of the symmetric nuclear matter, the above mentioned partial decay width observed are observed as 660, 647 and 521 keV, respectively at normal nuclear matter density. Furthermore, on moving from symmetric nuclear ($I = 0$) to asymmetric nuclear matter ($I = 0.5$) the above mentioned values shift to 662, 656 and 533 keV, respectively, for nuclear saturation density and zero temperature situation. Moreover, if we consider $D_{s0}(2317)$ meson decaying to $D_{s} + \pi$ mesons through $\eta - \pi^0$ mixing [69], then the observed vacuum values of the partial decay width was just 32 keV. Further, in normal nuclear matter density, $\rho_0$, and in cold symmetric nuclear medium, considering the mixing effect, the observed partial decay width enhance to 48 keV. This is because of enhanced decay channel caused by increase(decrease)in the masses of $D_{s0}(D_s)$ mesons. Also, on addition of hyperons along with the nucleons, at $\rho_B = \rho_0$, and $T = 0$, the decay width further increases to 56 keV.

We shall now compare the results of the in-medium decay width with the previous works. As far as our knowledge regarding the literature is concerned, in-medium partial decay width of above mentioned process have not been evaluated so far. However, using the quark model authors has predicted the vacuum value of partial decay width of $P$-wave scalar $D_0(2400)$ meson as 248 and 277 MeV, in ref. [70] and [71], respectively. Furthermore, in [69], authors used $^3P_0$ model to calculate the partial decay width of $D_s(2317)$ meson through the $\eta - \pi^0$ mixing as 32 keV in vacuum. Further, by taking $D_{s0}$ as four quark state authors observed its partial decay width to $D_s\pi$ as 6 keV [72]. Also, in [73] above mentioned width was observed as 21.5 keV, using full chiral theory on equating the mass gap of $0^+$ and $1^+$ states with $0^-$ and $1^-$ states. Moreover, by considering $D_{s0}$ state as $s_l^p = 1/2^+$ and using heavy quark symmetries along with Vector Meson Dominance ansatz, authors observed the value of $\Gamma_{D_{s0}^0}(D_{s0}) \approx 7$ keV [74]. Similar results of partial decay width of above mentioned process were observed as 10, 16 and 39 keV in Ref. [75], [76] and [77], respectively. From the above discussion we observe that the partial decay widths of scalar $D_0$ and $D_{s0}$ mesons are quite model dependent and need to verify in the future experiments.
VI. SUMMARY

We observed the positive(negative) shift in masses(decay constants) of scalar $D_0(2400)$ and $D_{s0}(2317)$ mesons, using chiral SU(3) model and QCD sum rules. Positive shift in mass of these mesons indicate that these meson may act as facilitators to the production of $J/\psi$ state in HIC experiments. This is because the threshold value of $D\bar{D}$ pair will be above the mass of excited charmonium states and thus, these charmonium states will decay to $J/\psi$ mesons instead of $D\bar{D}$ pairs. Also, these repulsive interactions indicate that the scalar $D_0/D_{s0}$ meson may not form bound states with the nucleons as well as with hyperons. The enhanced value of in-medium mass may have significant effect on the elliptic flow and nuclear modification factor, $R_{AA}$ of these scalar open charmed meson produced in HICs experiments. Furthermore, we take the in-medium mass of these scalar $D$ mesons as an application in $^3P_0$ model and evaluate their in-medium partial decay widths for the processes, $D_0(2400) \to D + \pi$ and $D_{s0}^*(2317) \to D_s + \pi$. We observe that, as the mass of scalar $D$ meson increase in the hyperonic (along with the nucleons) medium, this results in the significant increase in the corresponding partial decay widths.

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