

Transition magnetic moments for $\Delta \rightarrow p$ transition in asymmetric nuclear matter

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In the present work we calculate the transition magnetic moments for the radiative decays of Δ baryon to proton ($\Delta \rightarrow p$) in isospin asymmetric nuclear medium at finite temperature using chiral SU(3) quark mean field model. Within the framework of chiral SU(3) mean field model, the properties of baryons in asymmetric medium are modified through the exchange of scalar fields (σ, ζ, δ) and vector fields (ω, ρ). The isospin asymmetry of medium is taken into account via scalar-isovector field δ and vector iso-vector field ρ . We calculate the in-medium masses of quarks, proton and Δ baryon in asymmetric matter within the chiral SU(3) quark mean field model and use these as input in the chiral constituent quark (χ CQM) model to calculate the in-medium transition magnetic moments for ($\Delta \rightarrow p$) transition for different values of isospin asymmetry of hot and dense medium. For calculating the magnetic moments of baryons, contributions of valence quarks, quark sea and orbital angular momentum of quark sea are considered in these calculations.

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1. Introduction

Exploring the impact of finite density and temperature of hadronic matter on the in-medium properties of various mesons and baryons is of considerable interest. Different experimental programs are aimed to understand different regimes of QCD phase diagram and exploring the nature of phase transition from hadronic to QGP phase. The experimental facilities such large hadron collider (LHC) [1, 2] and relativistic heavy-ion collider (RHIC) [3–6] where heavy-ion collisions are performed at large center of mass energies investigate the QCD phase diagram at high temperature and low baryon densities. Complimentary to this, compressed baryonic matter (CBM) experiment of FAIR project [7, 8], NICA project of Nuclotron-based Ion Collider Facility (NICA) at Dubna [9, 10] and low energy beam scan programs (BES-I and BES-II) of RHIC [11–13] aim to investigate the QCD phase diagram at high baryon density and moderate temperature.

Electromagnetic properties of baryons such as their magnetic moments and electromagnetic form factors play significant role in understanding the non-perturbative QCD and exploring the structure of hadrons. EMC effect as observed by European Muon Collaboration provided the first clue that the properties of nucleons are modified in the nuclear medium [14] and this triggered the interest in understanding the behaviour of hadrons in the medium with finite baryon density. Various theoretical approaches, for examples, different quark models [15, 16], QCD sum rules [17], light cone QCD sum rule [18, 19], chiral perturbation theory [20], soliton model [21], chiral constituent quark model (χ CQM) [22, 23] etc. have been used to explore the magnetic moments and form factors of baryons. Interest has grown in exploring the electromagnetic properties of different baryons and mesons in dense hadronic medium [24–27]. Apart from the magnetic moments and electromagnetic form factors of given baryons, the transition magnetic moments also play a key role in revealing the internal structure and deformation in the structure of the baryons. The transition amplitudes for $\Delta^+ \rightarrow p\gamma$ transition contain the magnetic dipole (G_{M1}), electric quadrupole (G_{E2}), and coulomb quadrupole (G_{C2}) contributions and gives the information about the magnetic dipole moment, electric quadrupole moment and charge quadrupole moment, respectively. The transition magnetic moments of baryons have also been studied in the free space [28–30].

In the present work, we use the combined approach of chiral SU(3) quark mean field (CQMF) model [31] and χ CQM [32] to calculate the transition magnetic moment of $\Delta^+ \rightarrow p\gamma$ transition in the isospin asymmetric nuclear medium at finite temperature. The magnetic moments of baryons are calculated using the χ CQM and in-medium effects will be stimulated through CQMF model [33–37]. In the CQMF model, quarks are confined inside the baryons through a confining potential and interact through the exchange of scalar meson fields σ , ζ and δ and the vector fields ω and ρ . The properties of baryons, for example, their in-medium masses are expressed in terms of properties of constituent quark masses. The CQMF model has been used to study the properties of nuclear matter [31] and neutron stars [38]. CQMF model has also been used along with light quark model to study the pion and kaon structure in asymmetric nuclear matter [39–41]. The χ CQM considers the contribution of not only valence quarks, but also sea quarks and orbital angular momentum of sea quarks in calculating the magnetic moments of baryons [32].

Following is the outline of present work: In Sec. 2 we present the details of CQMF and χ CQM models. The results on the transition magnetic moments for $\Delta \rightarrow p$ transition are presented in Sec. 3.

2. Formalism

As discussed before, in the present manuscript we use the combined approach of CQMF model and χ CQM to study the in-medium transition magnetic moment. In Sec. 2.1 we shall discuss the details of CQMF model to calculate the in-medium masses of quarks and baryons. The χ CQM used to calculate the transition magnetic moments of baryons is discussed in Sec. 2.2.

2.1 Chiral SU(3) quark mean field model

The CQMF model is based on low energy properties of QCD and incorporates chiral symmetry and its spontaneous and explicit breaking [31]. As discussed before, the model consider quarks confined inside the baryons as degrees of freedom. The scalar fields σ, ζ and δ provide the attractive interactions, whereas the vector fields ω and ρ contribute to the repulsive. The thermodynamics of asymmetric nuclear medium with finite temperature and density can be studied using the thermodynamic potential

$$\Omega = -\frac{T}{(2\pi)^3} \sum_i \gamma_i \int_0^\infty d^3k \left\{ \ln \left(1 + e^{-[E_i^*(k) - v_i^*]/T} \right) + \ln \left(1 + e^{-[E_i^*(k) + v_i^*]/T} \right) \right\} - \mathcal{L}_M - \mathcal{V}_{\text{vac}}. \quad (1)$$

In above, $i = p, n$, $\gamma_i = 2$ is the degeneracy factor and $E_i^*(k) = \sqrt{M_i^{*2} + k^2}$. The effective chemical potential v_i^* of nucleons relates to free chemical potential v_i as [31]

$$v_i^* = v_i - g_\omega^i \omega - g_\rho^i I^{3i} \rho. \quad (2)$$

In Eq. (1), the term, \mathcal{L}_M consider the contributions from self-interactions of scalar and vector mesons as well as from the explicit symmetry breaking term of the model, i.e., $\mathcal{L}_M = \mathcal{L}_S + \mathcal{L}_V + \mathcal{L}_{\chi SB}$. Here, \mathcal{L}_S describes the self-interactions of scalar mesons and is given as

$$\begin{aligned} \mathcal{L}_S = & -\frac{1}{2} k_0 \chi^2 (\sigma^2 + \zeta^2 + \delta^2) + k_1 (\sigma^2 + \zeta^2 + \delta^2)^2 + k_2 \left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2 \delta^2 + \zeta^4 \right) \\ & + k_3 \chi (\sigma^2 - \delta^2) \zeta - k_4 \chi^4 - \frac{1}{4} \chi^4 \ln \frac{\chi^4}{\chi_0^4} + \frac{\xi}{3} \chi^4 \ln \left(\left(\frac{(\sigma^2 - \delta^2) \zeta}{\sigma_0^2 \zeta_0} \right) \left(\frac{\chi^3}{\chi_0^3} \right) \right). \end{aligned} \quad (3)$$

In case of vector mesons, within the CQMF, we have the interaction Lagrangian density

$$\mathcal{L}_{VV} = \frac{1}{2} \frac{\chi^2}{\chi_0^2} (m_\omega^2 \omega^2 + m_\rho^2 \rho^2) + g_4 (\omega^4 + 6\omega^2 \rho^2 + \rho^4). \quad (4)$$

The Lagrangian density $\mathcal{L}_{\chi SB}$ describing the explicit breaking of chiral symmetry is written as

$$\mathcal{L}_{\chi SB} = \frac{\chi^2}{\chi_0^2} \left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2} m_K^2 f_K - \frac{m_\pi^2}{\sqrt{2}} f_\pi \right) \zeta \right]. \quad (5)$$

In order to investigate the properties of isospin asymmetric nuclear matter at finite temperature and density we use the mean field approximation [31]. In Eq. (1), the term \mathcal{V}_{vac} is subtracted to have zero vacuum energy. The Dirac equation, under the influence of meson mean field, for the quark field Ψ_{qi} , is given as

$$\left[-i\vec{\alpha} \cdot \vec{\nabla} + \chi_c(r) + \beta m_q^* \right] \Psi_{qi} = e_q^* \Psi_{qi}, \quad (6)$$

where the subscripts q and i denote the quark q ($q = u, d, s$) in a baryon of type i ($i = n, p$) and $\vec{\alpha}$, β are the usual Dirac matrices. The effective quark mass m_q^* is defined as

$$m_q^* = -g_\sigma^q \sigma - g_\zeta^q \zeta - g_\delta^q I^{3q} \delta + m_{q0}, \quad (7)$$

where m_{q0} is zero for non-strange ‘ u ’ and ‘ d ’ quarks, whereas for strange ‘ s ’ quark $m_{q0} = \Delta m = 77$ MeV. Effective energy of particular quark under the influence of meson mean field is given as, $e_q^* = e_q - g_\omega^q \omega - g_\rho^q I^{3q} \rho$ [31]. The in-medium mass M_i^* of the baryon is written in term of effective energy E_i^* and spurious center of mass momentum $p_{i\text{cm}}^*$ [42], i.e.,

$$M_i^* = \sqrt{E_i^{*2} - p_{i\text{cm}}^{*2}}. \quad (8)$$

In above, E_i^* is related to effective energy of constituent quarks through relation $E_i^* = \sum_q n_{qi} e_q^* + E_{i\text{spin}}$, where $E_{i\text{spin}}$ is fitted to obtain correct masses of baryons in the vacuum. The thermodynamic potential defined by Eq. (1) is minimized with respect to the scalar fields σ , ζ and δ , the dilaton field, χ , and, the vector fields ω and ρ , i.e.,

$$\frac{\partial \Omega}{\partial \sigma} = \frac{\partial \Omega}{\partial \zeta} = \frac{\partial \Omega}{\partial \delta} = \frac{\partial \Omega}{\partial \chi} = \frac{\partial \Omega}{\partial \omega} = \frac{\partial \Omega}{\partial \rho} = 0. \quad (9)$$

The coupled system of non-linear equations as obtained above are solved for different values of baryon density, temperature and isospin asymmetry of the medium. We define the isospin asymmetry in the medium through $I_a = -\frac{\sum_i I_{3i} \rho_i}{\rho_B}$. Here I_{3i} denotes the 3rd component of isospin quantum number in the i^{th} baryon and ρ_B is the total baryonic density.

2.2 Chiral constituent quark model: $\Delta \rightarrow p$ transition magnetic moment

To obtain the magnetic moment for $\Delta \rightarrow p$ transition contributions of valence quarks, sea quarks and orbital angular momentum of sea quarks are taken into account. In χ CQM the internal constituent quark undergoes the emission of Goldstone boson and this further splits into the pair of quark-antiquark. [43]. The Lagrangian density $\mathcal{L} = g_8 \bar{q} \Phi q$ describes the interactions of quarks with Goldstone bosons, where Φ consists of octet of pseudoscalar mesons as well as pseudoscalar singlet η' , i.e.,

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta' \frac{\eta'}{4\sqrt{3}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta' \frac{\eta'}{4\sqrt{3}} & \alpha K^0 \\ \alpha K^- & \alpha \bar{K}^0 & -\beta \frac{2\eta}{\sqrt{6}} + \zeta' \frac{\eta'}{4\sqrt{3}} \end{pmatrix}. \quad (10)$$

The constraints $m_s > m_{u,d}$ and also non-degenerate masses of pseudoscalars, i.e., ($M_{\eta'} > M_{K,\eta} > M_\pi$) incorporate SU(3) symmetry breaking. Also, parameter $a = |g_8|^2$ denotes the transition probability of chiral fluctuation of the splitting $u(d) \rightarrow d(u) + \pi^{+(-)}$. Further, $a\alpha^2$, $a\beta^2$ and $a\zeta'^2$ represent the probabilities of transitions of $u(d) \rightarrow s + K^{-(0)}$, $u(d, s) \rightarrow u(d, s) + \eta$ and $u(d, s) \rightarrow u(d, s) + \eta'$, respectively [23, 44].

Total transition magnetic moment for $\Delta \rightarrow p$ transition in asymmetric nuclear medium is written as [32]

$$\mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right) = \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_V + \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_S + \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_O. \quad (11)$$

The individual contributions to the total magnetic moment are expressed in terms of quark magnetic moments μ_q^* and spin polarization Δq as

$$\begin{aligned} \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_V &= \sum_{q=u,d,s} \Delta q \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_V \mu_q^* \\ \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_S &= \sum_{q=u,d,s} \Delta q \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_S \mu_q^* \\ \mu^* \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_O &= \sum_{q=u,d,s} \Delta q \left(\Delta_{\frac{3}{2}^+ \rightarrow \frac{1}{2}^+} \right)_V \mu^* (q_+ \rightarrow). \end{aligned} \quad (12)$$

The nuclear medium effects are introduced in the above equation through the effective quark magnetic μ_q^* , which individually for u, d and s quarks are defined as

$$\mu_d^* = - \left(1 - \frac{\Delta M}{M_B^*} \right), \quad \mu_s^* = - \frac{m_u^*}{m_s^*} \left(1 - \frac{\Delta M}{M_B^*} \right), \quad \mu_u^* = -2\mu_d^*. \quad (13)$$

The above definitions for the calculations of magnetic moments of quarks are motivated to incorporate the confinement effects [44]. Here, $\Delta M = M_{vac} - M_B^*$ and also, M_{vac} and M_B^* are the vacuum and in-medium masses of initial state baryon. The effective mass of baryons is calculated using Eq.(8). The factor $\mu^* (q_+ \rightarrow)$ consider the contribution of orbital moment of chiral fluctuations and is expressed in terms of transition probabilities and masses of Goldstone bosons. In Ref. [32], the transition magnetic moment for $\Delta \rightarrow p$ transition are calculated in the free space.

3. Results and discussion

In this section, we discuss the results on the in-medium transition magnetic moments for $\Delta \rightarrow p$ transition calculated using the χ CQM and incorporating the medium effects through the CQMF model. As described previously, the effective constituent quark masses and masses of baryons are calculated using the CQMF model and are used as input in χ CQM. The isospin asymmetric effects are introduced through the asymmetry parameter I_a . For a given asymmetry and temperature of the medium, the effective quark masses are observed to decrease as the baryon density is increased. The decrease in the mass of quarks becomes slightly slower as value of I_a is increased from zero to finite value. Finite value of I_a also causes the mass splitting between the masses of u and d quarks due to non-zero value of scalar-isovector δ field in asymmetric nuclear medium. The details about the magnitude of changes in effective masses of constituent quarks and baryons in asymmetric nuclear medium can be found in Refs. [33–35]. In the current work, we present the results on transition magnetic moments. In Fig. 1a, we plot the net transition magnetic moment for $\Delta \rightarrow p$ transition as a function of baryons density ratio ρ_B/ρ_0 . The results are shown for temperature $T = 0$ and isospin asymmetry parameter $I_a = 0, 0.3$ and 0.5 . As can be seen, an increase in the baryon density of medium causes a decrease in the value of $\mu^* (\Delta \rightarrow p)$. For a given density, increasing the value of I_a from zero to 0.5 causes an increase in $\mu^* (\Delta \rightarrow p)$. The impact of isospin asymmetry is

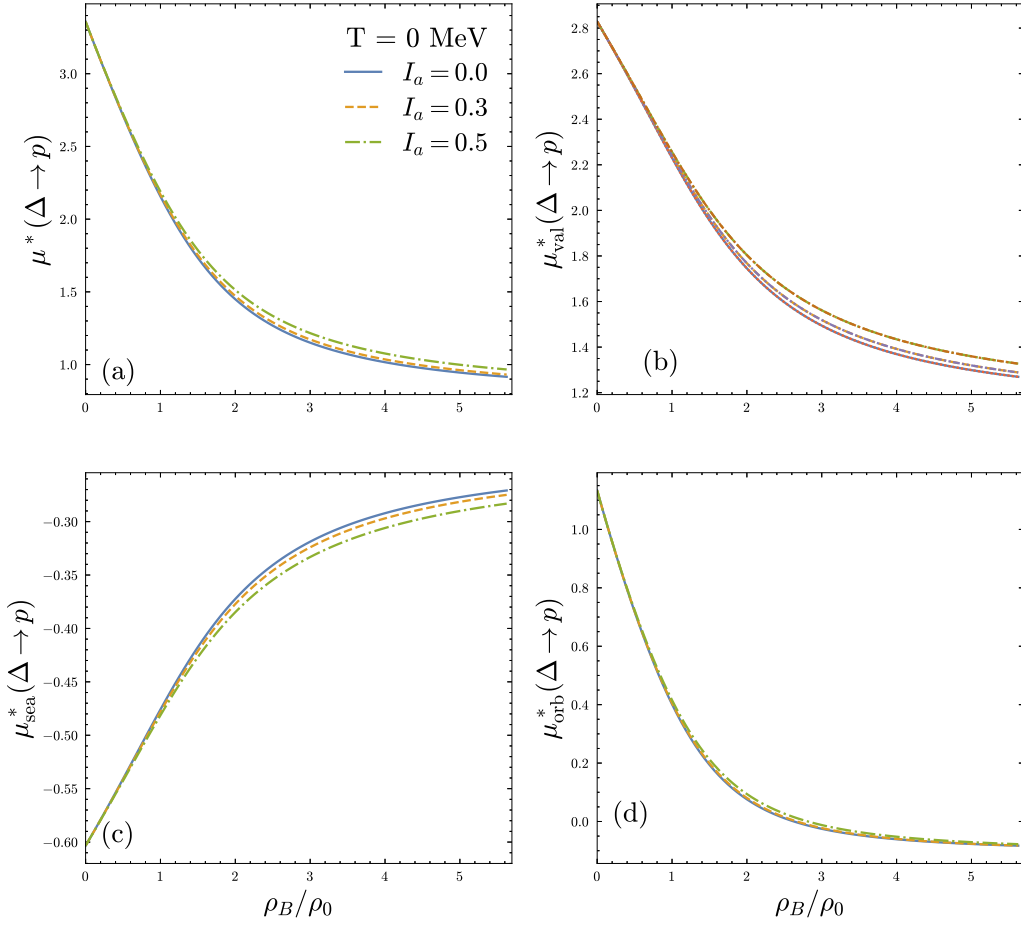


Figure 1: In above, (a) transition magnetic moment for $\Delta \rightarrow p$, (b) contribution of valence quarks, (c) sea quarks and (d) orbital angular momentum of sea quarks is shown as a function of baryon density ρ_B (in units of ρ_0) of nuclear matter at temperature $T = 0$ MeV and isospin asymmetry $I_a = 0, 0.3$ and 0.5 .

found to be more appreciable at large baryon density of the medium. In symmetric nuclear medium ($I_a = 0$), as baryon density is increased from zero to ρ_0 ($3\rho_0$), the value of $\mu^*(\Delta \rightarrow p)$ decreases by 35.71%(65.77%). Increasing I_a to 0.5, these values at ρ_0 ($3\rho_0$) change to 34.82%(63.69%). For better understanding, in Fig. 1(b), (c) and (d), the individual contributions to total magnetic moment from valence quarks, sea quarks and orbital angular momentum of sea quarks, respectively, are shown. The magnitude of all three contribution decrease as a function of density of the medium. As a function of I_a , magnetic moment contributions from valence quarks increase, whereas from sea quarks become more negative. In terms of magnitude, changes are observed to be largest in case of valence quark, i.e., Fig. 1b. At temperature $T = 100$ MeV, the values of magnetic moment, as ρ_B changes from vacuum to ρ_0 ($3\rho_0$), decreases by 30.65%(61.31%) at $I_a = 0$, whereas at $I_a = 0.5$ these values change to 30.36% (60.42%). The present work of in-medium transition magnetic moments will be extended to other transitions from decuplet to octet baryons in future work.

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