

Spacelike Sachs electric and magnetic form factors of the baryons in the asymmetric nuclear medium

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In the present work, we have studied the spacelike baryon Sachs form factors in the isospin asymmetric nuclear medium using the vector-meson dominance (VMD) model. The in-medium effects are incorporated through the medium-modified masses of vector mesons which are calculated using the QCD sum rule approach, taking density-dependent scalar quark and gluon condensates as inputs from chiral SU(3) quark mean-field (CQMF) model. The effective magnetic moments of the baryons are also calculated in the CQMF model. In the framework of the VMD model, the photon couples to the nucleons through intermediary vector mesons with the same quantum number as that of a photon. This coupling leads to the relation of isoscalar and isovector Dirac and Pauli form factors which are then used to calculate the Sachs electric and magnetic form factors, which provide physically measurable quantities that represent the electric and magnetic distributions of the baryons. The present work aims to study the effects of asymmetric nuclear matter at finite temperature on the Sachs form factors of baryons in the spacelike region. The electric and magnetic charge radii have also been calculated for the baryons in free space and dense asymmetric nuclear matter. The results obtained have been compared with other available phenomenological models, lattice simulations, and experimental data.

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I. INTRODUCTION

One of the core objectives of hadron physics is to understand the fundamental constituents of matter and the interactions among them. In this context, the internal structure of the nucleons and other baryons remains a subject of fundamental significance. Form factors of the baryons [1–8] provide valuable insights into the internal distributions of quarks and gluons and serve as a probe of its structure responsible for generating their electromagnetic properties. The deep inelastic scattering experiments performed by the MIT-SLAC Collaboration provided strong evidence for the existence of quarks inside nucleons [9]. A historical account of the discovery of quarks is presented in Ref. [10]. While observing the European Muon Collaboration (EMC) effect, which refers to the modification of the parton distributions of nucleons bound

in nuclei, the nucleon structure functions deviate from those of free nucleons [11]. The electromagnetic form factors (EMFFs) of the nucleons offer a direct probe to their internal structure and the corresponding modifications inside the nuclear environment. Despite being neutral, Sachs form factors of the neutrons reveal asymmetric quark distributions, with a negative value of the charge radii and magnetic form factors providing key insights into strong-interaction dynamics [12].

Sachs form factors in the spacelike region ($Q^2 > 0$) are measured in elastic electron-nucleon scattering experiments. The experimental determination of spacelike form factors requires specialized electron-scattering facilities as the measurements become increasingly difficult at high momentum transfer due to very small scattering cross sections. In the timelike region ($Q^2 < 0$), Sachs form factors are studied through the creation or annihilation of nucleon-antinucleon pairs, such as in $e^+e^- \rightarrow N\bar{N}$ and $\bar{p}p \rightarrow e^+e^-$ processes. Timelike form factors, on the other hand, are investigated through hadron production processes in the timelike region [13]. These observables connect experimental measurements with theoretical descriptions of hadronic structure across different physical environments. The vacuum EMFFs for both time- and spacelike regions for the nucleons have been studied widely and act as input for the precision tests of the standard model to determine fundamental constants. They are of critical importance for the accelerator neutrino program.

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Form factors of baryons have been studied widely in both the space- and timelike regions, using a large range of theoretical frameworks. These include first-principles approaches such as lattice QCD, where axial form factors have been computed using various lattice formulations and averaging procedures, as well as through the Feynman-Hellmann theorem and domain-wall fermions on highly improved staggered quark ensembles [14]. Parallel approaches involve generalized nonlocal chiral effective theory, dispersively modified chiral perturbation theory, and models based on the Skyrme model [15,16]. In addition to this, relativistic descriptions such as the Poincaré-covariant quark-diquark framework employing Faddeev equations have been widely used [17].

Form factors have also been extracted from generalized parton distributions, including recent parametrizations (e.g., GSAMA24), and analyzed through their t dependence in parton distribution functions, short-range correlations, and the EMC effect [18–20]. Related studies include tensor form factors at large N_e , electric dipole form factors in the QCD vacuum, and calculations based on extended vector-meson dominance (VMD), pion cloud effects, and hard collinear factorization for gravitational form factors [21–23]. Further results have been obtained from nucleon resonance transition form factors, toy models explaining oscillatory behavior in the timelike region, diagrammatic analyses involving bubble and tadpole contributions, and holographic approaches such as the hard-wall AdS/QCD model [24–27].

Experimental facilities such as the Relativistic Heavy Ion Collider and the Large Hadron Collider probe strongly interacting matter at high temperature and nearly zero baryon density. On the other hand, experiments such as the Facility for Antiproton and Ion Research, the J-PARC facility at KEK, and NICA at Dubna are dedicated to exploring the high baryon-density regime [28,29]. From a theoretical perspective, hadronic models such as quantum hadrodynamics, the quark-meson coupling model [30], the Nambu–Jona-Lasinio (NJL) model [31], lattice QCD [32], the VMD model, chiral effective field theory [33], covariant quark-diquark models [34], quark-diquark Faddeev approaches [35], and light-front constituent quark models [36] have been widely employed to investigate medium-induced modifications of hadron properties at finite temperature and density.

The study of the hyperons, which contain strange quarks, is of vital importance as their EMFFs provide additional insights into nonperturbative QCD effects [32,33,37–40] compared to what has been learned from the nucleons. In the timelike region, EMFFs of the Σ hyperon have been studied by BESIII Collaboration [39]. In addition to this, the hyperon EMFFs have been calculated within the lattice QCD [32], light-cone sum rule [41], and chiral perturbative theory [42]. Form factors of hyperons such as the Λ baryon have been relatively less explored, notably in the spacelike

region, primarily due to experimental limitations associated with their short lifetimes. Most of the available studies focus on the timelike region, including dispersion-theoretical analyses of EMFFs, VMD-based transition form factors, and investigations at large momentum transfer. Overall, while nucleon form factors are well constrained across both kinematic regions, hyperon form factors—especially in the spacelike domain—remain comparatively underexplored and are largely theory driven.

The VMD [43] model provides an effective phenomenological framework in which the photon couples to a baryon through intermediate vector mesons. The resulting Sachs form factors encode the dressing of both the photon-vector-meson and vector-meson-baryon vertices. In an effective sense, they incorporate contributions arising from the internal quark-gluon structure, meson clouds, and other higher-order strong-interaction effects. Based on the recent measurements of the $e^+e^- \rightarrow \Sigma^+\bar{\Sigma}^-$ and $e^+e^- \rightarrow \Sigma^-\bar{\Sigma}^+$ processes by BESIII Collaboration, the parameters of the VMD model have been determined by fitting them to the experimental data on the timelike effective form factors ($|G_{\text{eff}}|$). In the current work, for Σ^+ and Σ^- hyperons, we have included the contributions from the ρ , ω , and ϕ mesons to account for the photon-vector-meson coupling effects. Within this work, we have also studied the Sachs form factors of the Λ hyperon, where we have taken into account the contributions from the resonance states $\omega(1420)$, $\omega(1650)$, $\phi(1680)$, and $\phi(2170)$ [37].

The Λ hyperon, being electrically neutral, has a small electric form factor and highly sensitive internal dynamics. Resonance states appear naturally in the VMD diagram via $\gamma^* \rightarrow V(\rho, \omega, \phi) \rightarrow \Lambda^* \rightarrow \Lambda$. The Λ hyperon contain an s quark and hence the ϕ meson couples strongly to these hyperons, thus making the resonances quantitatively significant at low- and intermediate- Q^2 behavior. The inclusion of these resonance states, together with the ground-state contributions, thus provides a more accurate and improved description of the form factor behavior. It also gives better nonperturbative QCD effects, which are absent in the pure ground-state model. Additionally, in the nuclear medium, vector-meson masses [44] and widths are modified, which enhances the resonance contributions and makes their effect more pronounced.

The medium modifications of light hadrons are closely connected to the spontaneous and explicit breaking of chiral symmetry and its restoration at high temperatures and baryon densities. The present study aims to bridge these approaches to provide a coherent description of the electromagnetic structure of baryons. The current work of the in-medium meson masses and magnetic moments of the baryons provides phenomenological input and acts as a bridge between nonperturbative QCD and experimental data from the Large Hadron Collider beauty experiment [45] and the future Electron-Ion Collider (EIC) [46]. In this context, the present work aims to address these existing

gaps by extending these models to investigate the internal dynamics of the hadrons in a dense nuclear environment.

In the current study, we have focused on the spacelike Sachs form factors of the nucleons [47], as well as hyperons within an asymmetric nuclear medium at finite temperatures and their comparison with Sachs form factors in free space. These form factors are evaluated using the VMD model, where in-medium effects are incorporated by accounting for the modifications in the masses of light vector mesons as well as the effective magnetic moments of the baryons. The effective masses of vector mesons are determined through the QCD sum rule approach [48], while the effective magnetic moments are calculated in the quark mean-field (CQMF) model [49,50]. The CQMF model is an effective approach in which baryons are described as bound states of constituent quarks interacting with scalar and vector-meson fields in a mean-field approximation, hence the key aspects of QCD and chiral symmetry breaking are incorporated. Within this framework, quarks satisfy the Dirac equation in the presence of background meson fields, such as the scalar-isoscalar field σ , the scalar-strange field ζ , the vector-isoscalar field ω , and the vector-isovector field ρ . The chiral condensates, such as $\langle \bar{q}q \rangle$ and $\langle \bar{s}s \rangle$, are directly related to the scalar fields σ and ζ , which act as order parameters of chiral symmetry. The values of these condensates are obtained by constructing the thermodynamic potential, thereby minimizing it with respect to these scalar fields. Solving the coupled non-linear equations, the solutions provide the density and temperature dependence of the condensates, thereby reflecting the partial restoration of chiral symmetry in hot and dense matter. The in-medium masses are obtained from the QCD sum rules and, within the VMD framework, the vacuum and in-medium form factors are calculated, which are then used to evaluate the root-mean-square electric and magnetic charge radii. These electric and magnetic charge radii values at vacuum have been compared with available experimental and theoretical results.

The present work has been organized as follows: In Sec. II, the model framework, used to calculate fields, condensates, and the in-medium masses of the light vector mesons, as well as the framework used to calculate the Dirac and Pauli form factors and, hence, the Sachs form factors of the baryons, have been detailed. In Sec. III, the results and discussions of the Sachs form factors have been presented, and Sec. IV summarizes the important findings of the present work.

II. METHODOLOGY

In this section, the theoretical framework for studying the effect of the asymmetric nuclear medium at finite temperature on the Sachs form factors of nucleons and hyperons is presented. In Sec. II A, we have discussed the CQMF model for the calculations of in-medium scalar quark and

gluon condensates. In Sec. II B, the QCD sum rule to calculate the effective masses of the light vector mesons has been presented. Finally, in Sec. II C, the VMD model is described for calculating the effective form factors of the baryons.

A. Chiral SU(3) quark mean-field model

In this section, we describe the CQMF model, which has been used to study the in-medium properties of the condensates. The model is based on the spontaneous and explicit breaking of chiral symmetry and also takes into account low-energy QCD properties [51,52]. In this model, through a confining potential, quarks are bound inside the baryons and interact via the exchange of scalar fields σ and ζ . The contribution of the scalar-isovector δ field becomes significant when the medium has a finite isospin asymmetry. The total effective Lagrangian density in the CQMF model is written as [53]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{q0} + \mathcal{L}_{qm} + \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{vv} + \mathcal{L}_{\chi sb} + \mathcal{L}_C. \quad (1)$$

The first term, $\mathcal{L}_{q0} = \bar{q}i\gamma^\mu \partial_\mu q$ is the quark's kinetic term. The second term, $\mathcal{L}_{qm}$ describes the interactions of constituent quarks with the scalar and vector mesons [49,53]. The third term $\mathcal{L}_{\Sigma\Sigma}$ is the self-interaction of scalar mesons (σ , ζ , and δ) and the dilaton field χ [53,54]. The fourth term gives the self-interactions of vector mesons ω and ρ , and the term $\mathcal{L}_{\chi sb}$ represents the explicit symmetry breaking. The last term corresponds to the confinement of quarks inside the baryons and is defined as

$$\mathcal{L}_C = -\bar{\Psi}\chi_c\Psi. \quad (2)$$

Here, $\chi_c(r) = \frac{1}{4}k_c r^2(1 + \gamma^0)$ is the confining potential, where the coupling constant k_c is taken as 98 MeV fm^{-2} [53]. To study the properties of isospin asymmetric nuclear matter at finite temperature and baryonic density, we have used the mean-field approximation. The Dirac equation, under the influence of meson mean fields, for the quark field Ψ_{qj} , is given as [53]

$$[-i\vec{\alpha} \cdot \vec{\nabla} + \chi_c(r) + \beta m_q^*]\Psi_{qj} = e_q^* \Psi_{qj}. \quad (3)$$

Here, subscripts q and j denote the quark q ($q = u, d$) in a nucleon of type j ($j = p, n$) in the nuclear medium and m_q^* is the effective quark mass. In terms of the third component of the isospin of the respective quark, I^3_q , the effective energy of a particular quark under the influence of the meson field can be expressed as

$$e_q^* = e_q - g_\omega^q \omega - g_\rho^q I^3_q \rho. \quad (4)$$

Within the CQMF model, the effective mass $\mathcal{M}_j^*$ of the j^{th} baryon is related to the effective energy $\mathcal{E}_j^*$ and

in-medium spurious center-of-mass momentum $P_{jc.m.}^*$ [55,56] through

$$\mathcal{M}_j^* = \sqrt{\mathcal{E}_j^{*2} - \langle P_{jc.m.}^{*2} \rangle}. \quad (5)$$

The effective energy $\mathcal{E}_j^*$ of baryons can also be expressed in terms of the effective energy of constituent quarks e_q^* using relation

$$\mathcal{E}_j^* = \sum_q n_{qj} e_q^* + \mathcal{E}_{j\text{spin}}. \quad (6)$$

In the above equation, n_{qj} denotes the number of quarks of type q present in the j th nucleon of medium. Further, the term $\mathcal{E}_{j\text{spin}}$ contributes as a correction to nucleon energy due to spin-spin interaction, which is fitted to the vacuum masses of baryons.

The thermodynamic potential for the isospin asymmetric nuclear matter at finite temperature is

$$\Omega = -\frac{k_B T}{(2\pi)^3} \sum_j \alpha_j \int_0^\infty d^3 k' \left\{ \ln \left(1 + e^{-[\mathcal{E}_j^*(k') - \beta_j^*]/k_B T} \right) + \ln \left(1 + e^{-[\mathcal{E}_j^*(k') + \beta_j^*]/k_B T} \right) \right\} - \mathcal{L}_M - \mathcal{V}_{\text{vac}}, \quad (7)$$

where the summation is over the nucleons ($j = p, n$), $\alpha_j = 2$ is the degeneracy factor, and β_j^* is the effective chemical potential. Also, $\mathcal{L}_M = \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{vv} + \mathcal{L}_{\chi sb}$ and $\mathcal{E}^*(k') = \sqrt{\mathcal{M}_j^{*2} + k'^2}$. The term $\mathcal{V}_{\text{vac}}$ is subtracted to obtain zero vacuum energy [50,53]. The thermodynamic potential as mentioned in Eq. (7) is minimized with respect to the scalar fields σ , ζ , and δ , dilaton field χ , and vector fields ω and ρ . Solving the coupled mean-field equations, in-medium meson field expectation values are calculated, which are further used to obtain effective constituent quark masses, quark and gluon condensates, and effective magnetic moments of baryons.

The nonstrange quark condensates $\langle u\bar{u} \rangle$ and $\langle d\bar{d} \rangle$ and the strange quark condensate $\langle s\bar{s} \rangle$ are related to the scalar fields σ , ζ , δ and the scalar dilaton field χ as

$$m_u \langle u\bar{u} \rangle = \frac{1}{2} m_\pi^2 f_\pi (\sigma + \delta), \quad (8)$$

$$m_d \langle d\bar{d} \rangle = \frac{1}{2} m_\pi^2 f_\pi (\sigma - \delta), \quad (9)$$

$$m_s \langle s\bar{s} \rangle = \left(\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta, \quad (10)$$

$$\begin{aligned} & \left\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^a G^{a\mu\nu} \right\rangle \\ &= \frac{8}{9} \left[(1-d)\chi^4 + \left(m_\pi^2 f_\pi \sigma + \left(\sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta \right) \right]. \end{aligned} \quad (11)$$

The values of the constants are $m_\pi = 139$, $f_\pi = 92.8$, $m_k = 494$, and $f_k = 115$ MeV. For massless quarks, the scalar gluon condensate is proportional to the fourth power of the dilaton field χ , but for finite mass, modification arises from the scalar fields σ and ζ . The condensates have been used to calculate the medium-dependent masses of the light vector mesons ω , ρ , and ϕ using the QCD sum rule approach.

B. QCD sum rules approach

In the present section, the properties of the vector mesons are studied using QCD sum rules in the nuclear medium [57]. The current correlation function for the vector mesons in terms of the time-ordered product is written as

$$\Pi_{\mu\nu} = i \int d^4 x d^4 y \langle 0 | T j_\mu^v(x) j_\nu^v(0) | 0 \rangle, \quad (12)$$

where T is the time-ordered product and j_μ^v is the current for the vector mesons, $j_\mu^\rho = \frac{1}{2} (\bar{u} \gamma_\mu u - \bar{d} \gamma_\mu d)$, $j_\mu^\omega = \frac{1}{6} (\bar{u} \gamma_\mu u + \bar{d} \gamma_\mu d)$, and $j_\mu^\phi = -\frac{1}{3} (\bar{s} \gamma_\mu s)$ [58,59]. We express the correlation function in the spacelike region for the light vector mesons in terms of the operator product expansion (OPE). Each term of the OPE contains the coefficient c_i^v with information of the nonperturbative effects of QCD [58]. For the ϕ meson, these coefficients are defined as

$$c_0^\phi = 1 + \frac{\alpha_s(Q^2)}{\pi}, \quad c_1^\phi = -6m_s^2, \quad (13)$$

$$c_2^\phi = \frac{\pi^2}{3} \left\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu} \right\rangle + 8\pi^2 \langle m_s \bar{s}s \rangle, \quad (14)$$

$$\begin{aligned} c_3^\phi = & -8\pi^3 \left[2 \langle \alpha_s (\bar{s} \gamma_\mu \gamma_5 \lambda^a s)^2 \rangle \right. \\ & \left. + \frac{4}{9} \left\langle \alpha_s (\bar{s} \gamma_\mu \lambda^a s) \left(\sum_{q=u,d,s} \bar{q} \gamma^\mu \lambda^a q \right) \right\rangle \right]. \end{aligned} \quad (15)$$

For the vector mesons ρ and ω ,

$$c_0^{(\rho,\omega)} = 1 + \frac{\alpha_s(Q^2)}{\pi}, \quad c_1^{(\rho,\omega)} = -3(m_u^2 + m_d^2), \quad (16)$$

$$c_2^{(\rho,\omega)} = \frac{\pi^2}{3} \left\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu} \right\rangle + 4\pi^2 \langle m_u \bar{u}u + m_d \bar{d}d \rangle, \quad (17)$$

$$c_3^{(\rho,\omega)} = -4\pi^3 \left[\langle \alpha_s (\bar{u}\gamma_\mu\gamma_5\lambda^x u \mp \bar{d}\gamma_\mu\gamma_5\lambda^x d)^2 \rangle + \frac{2}{9} \left\langle \alpha_s (\bar{u}\gamma_\mu\lambda^a u + \bar{d}\gamma_\mu\lambda^a d) \left(\sum_{q=u,d,s} \bar{q}\gamma^\mu\lambda^x q \right) \right\rangle \right]. \quad (18)$$

In the above equation, $\alpha_s = 4\pi/(y \ln(Q^2/\Lambda_{\text{QCD}}^2))$ is the running coupling constant, with $\Lambda_{\text{QCD}} = 140$ MeV and $y = 11 - (2/3)N_f = 9$. In Eq. (18), the “ $\mp$ ” sign in the first term corresponds to ρ and ω mesons, respectively. Comparing the correlator for the vector meson from the Borel transformation on the phenomenological side and expanding a few terms from the operator product expansion [59,60], we get the finite energy sum rules (FESRs) for the vector mesons. Using the finite energy sum rules, factorization method [61], and quark condensates, the coefficient c_3 for ρ and ω vector mesons is given as

$$c_3^{(\rho,\omega)} = -\alpha_s \pi^3 \times \frac{448}{81} \kappa_q (\langle \bar{u}u \rangle^2 + \langle \bar{d}d \rangle^2), \quad (19)$$

where $\kappa_u \simeq \kappa_d = \kappa_q$. For the ϕ meson,

$$c_3^\phi = -8\pi^3 \times \frac{224}{81} \alpha_s \kappa_s \langle \bar{s}s \rangle^2. \quad (20)$$

From the Borel transformation of the spectral functions as discussed earlier, we obtain the finite sum rules for vacuum, which are given as [59,60]

$$H_v = d_v (c_0^v s_0^v + c_1^v), \quad (21)$$

$$H_v m_v^2 = d_v \left(\frac{(s_0^v)^2 c_0^v}{2} - c_2^v \right), \quad (22)$$

$$H_v m_v^4 = d_v \left(\frac{(s_0^v)^3}{3} c_0^v + c_3^v \right). \quad (23)$$

Equations (21)–(23) are fitted to the vacuum masses of the mesons to find the vacuum values of the four-quark condensates c_3^v and the value of k_v . Here, $d_v = \frac{3}{2}, \frac{1}{6}$, and $\frac{1}{3}$ for ρ , ω , and ϕ mesons, respectively. At nonzero baryon densities, the spectral function of vector mesons acquires an additional contribution due to their scattering with baryons present in the medium. Consequently, the Borel-transformed dispersion relation for the vector mesons is modified as

$$\int_0^\infty ds e^{-s/M^2} R_{\text{phen}}^v(s) + 12\pi^2 \Pi^v(0) = d_v \left[c_0^v M^2 + c_1^v + \frac{c_2^v}{M^2} + \frac{c_3^v}{2M^4} \right], \quad (24)$$

where the additional term $\Pi^v(0)$ denotes the forward scattering amplitude of the vector meson v in the medium and M is the Boreal mass. In nuclear matter, the forward scattering amplitude can be written as

$$\Pi^{\omega,\rho}(0) = \frac{\rho_j}{4\mathcal{M}_N^*}. \quad (25)$$

For the ϕ meson it vanishes as the ϕ -nucleon coupling is negligible. The coefficients c_0^v and c_1^v in Eq. (16) remain independent of the medium, whereas c_2^{v*} and c_3^{v*} depend explicitly on the in-medium quark and gluon condensates, as defined by Eqs. (17)–(20). The medium modification of the vector-meson spectral function arises from the change in both condensates and the additional scattering term $\Pi^v(0)$, reflecting the baryonic composition of the system. In the text, c_2^{v*} , c_3^{v*} , and s_0^{v*} are being used to depict the medium-dependent effects. At finite densities, FESR for the vacuum is modified to

$$H_v^* = d_v (c_0^v s_0^{v*} + c_1^v) - 12\pi^2 \Pi^v(0), \quad (26)$$

$$H_v^* m_v^{*2} = d_v \left(\frac{(s_0^{v*})^2 c_0^v}{2} - c_2^{v*} \right), \quad (27)$$

$$H_v^* m_v^{*4} = d_v \left(\frac{(s_0^{v*})^3}{3} c_0^v + c_3^{v*} \right). \quad (28)$$

We have simultaneously solved these equations to obtain the values of m_v^* , s_0^{v*} , H_v^* using the coefficient k_v of the four-quark condensate for the vector mesons as determined from the FESR rules in vacuum.

C. Vector-meson dominance model

In the present section, we will calculate the EMFFs of the baryons taking in-medium magnetic moments from the CQMF model and in-medium masses of the light vector mesons from the QCD sum rules. Relativistic invariance allows the nucleon current to be expressed in terms of the Dirac form factor F_1 and the Pauli form factor F_2 through the following relation [47]:

$$J^\mu = \gamma^\mu F_1(Q^2) + i \frac{\sigma^{\mu\nu} F_2(Q^2) q_\nu}{2\mathcal{M}_b}, \quad (29)$$

where $\mathcal{M}_b$ denotes the mass of the baryon, $b = p, n, \Sigma^\pm, \Lambda$, q_ν is the four-momentum transfer, and $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$.

In the framework of the VMD model, the coupling of photon to the nucleon occurs indirectly through the exchange of light vector mesons [62]. These interactions lead to relations connecting the electric and magnetic “Sachs form factors” of the nucleon, G_E and G_M , respectively, with the isoscalar F^{S*} and isovector F^{V*} form factors. We have

$$G_M^{p*} = (F_1^{S*} + F_1^{V*}) + (F_2^{S*} + F_2^{V*}), \quad (30)$$

$$G_E^{p*} = (F_1^{S*} + F_1^{V*}) - \tau_p(F_2^{S*} + F_2^{V*}), \quad (31)$$

$$G_M^{n*} = (F_1^{S*} - F_1^{V*}) + (F_2^{S*} - F_2^{V*}), \quad (32)$$

$$G_E^{n*} = (F_1^{S*} - F_1^{V*}) - \tau_n(F_2^{S*} - F_2^{V*}). \quad (33)$$

In the VMD model [62], the Dirac form factor receives contributions from both the intrinsic three-quark structure and the meson cloud, whereas the Pauli form factor is largely dominated by the meson cloud. Taking into consideration the dimensional counting rules [63,64] and perturbative QCD (p-QCD), the term of the type $g(Q^2) = 1/(1 + \gamma Q^2)^2$ is introduced in F_2^{V*} and $\tau_b = Q^2/4M_b^2$. Using these, the expressions for isoscalar and isovector Dirac and Pauli form factors are expressed as [65]

$$\begin{aligned} F_1^{S*}(Q^2) &= \frac{1}{2}g(Q^2) \left[1 - \beta_\omega - \beta_\phi + \beta_\omega \frac{m_\omega^{*2}}{m_\omega^{*2} + Q^2} \right. \\ &\quad \left. + \beta_\phi \frac{m_\phi^{*2}}{m_\phi^{*2} + Q^2} \right], \\ F_1^{V*}(Q^2) &= \frac{1}{2}g(Q^2) \left[1 - \beta_\rho + \beta_\rho \frac{m_\rho^{*2}}{m_\rho^{*2} + Q^2} \right], \\ F_2^{S*}(Q^2) &= \frac{1}{2}g(Q^2) \left[(\mu_p^* + \mu_n^* - 1 - \alpha_\phi) \frac{m_\omega^{*2}}{m_\omega^{*2} + Q^2} \right. \\ &\quad \left. + \alpha_\phi \frac{m_\phi^{*2}}{m_\phi^{*2} + Q^2} \right], \\ F_2^{V*}(Q^2) &= \frac{1}{2}g(Q^2) \left[\frac{\mu_p^* - \mu_n^* - 1 - \alpha_\rho}{1 + \gamma Q^2} + \alpha_\rho \frac{m_\rho^{*2}}{m_\rho^{*2} + Q^2} \right]. \end{aligned} \quad (34)$$

The effective magnetic moments μ_p^* and μ_n^* of the nucleons appearing in the above equation have been calculated within the CQMF model, which includes the contribution from valence quarks, sea quarks, and orbital quarks [54,66].

The values of the meson masses are taken as $m_\rho = 0.770$, $m_\omega = 0.783$, and $m_\phi = 0.783$ GeV, while the values of the constants used in the calculations of the Sachs form factors of the nucleons are $\beta_\rho = 0.512$, $\beta_\omega = 1.129$, $\beta_\phi = -0.263$, $\alpha_\rho = 2.675$, $\alpha_\phi = -0.200$, and $\gamma = 0.515$ (GeV/c)⁻² [65]. The decay width of the ρ meson is crucial for the small Q^2 behavior of the form factors and is taken into account through the replacement [62,67]

TABLE I. The parameter values used for the calculation of the $\Sigma^\pm$ baryon's Sachs form factors [70].

Parameter	Value	Parameter	Value
β_ρ	0.736	α_ρ	0.976
β_ϕ	-0.441	α_ϕ	1.035
β_ω	0.434	γ_1	0.46
γ_2	1.18		

$$\frac{m_\rho^{*2}}{m_\rho^{*2} + Q^2} \rightarrow \frac{m_\rho^{*2} + \frac{8\Gamma_\rho^* m_\pi^*}{\pi}}{m_\rho^{*2} + Q^2 + (4m_\pi^{*2} + Q^2) \frac{\Gamma_\rho^* \alpha(Q^2)}{m_\pi^*}}, \quad (35)$$

with

$$\alpha(Q^2) = \frac{2}{\pi} \sqrt{\frac{4m_\pi^{*2} + Q^2}{Q^2}} \ln \left(\frac{\sqrt{4m_\pi^{*2} + Q^2} + \sqrt{Q^2}}{2m_\pi^*} \right). \quad (36)$$

The in-medium decay width Γ_ρ^* [68] is calculated using

$$\Gamma_\rho^* = \frac{g_{\rho\pi\pi}^2}{48\pi} m_\rho^* \left(1 - \frac{4m_\pi^{*2}}{m_\rho^{*2}} \right)^{3/2} (X^2 - Y^2). \quad (37)$$

In the above equation, $X = (1 + f(\frac{m_\rho^*}{2}))$ and $Y = f(\frac{m_\pi^*}{2})$. The function $f(\frac{m_\rho^*}{2}) = \exp(\frac{m_\rho^*}{2(T-1)})^{-1}$ represents the Bose-Einstein distribution function [69]. The coupling constant $g_{\rho\pi\pi}$ is fixed to the vacuum value of the decay width 0.112 GeV of the ρ meson. For the $\Sigma^\pm$ hyperon, the Dirac and Pauli form factors have been calculated by taking intrinsic form factors $g_1(Q^2) = (1 + \gamma_1 Q^2)^{-2}$ and $g_2(Q^2) = (1 + \gamma_2 Q^2)^{-2}$ [70].

The free model parameters γ_1 and γ_2 as well as other constants used in the calculations of Sachs form factors of $\Sigma^\pm$ hyperons are presented in Table I [70]. The Sachs form factors for the $\Sigma^\pm$ baryon are given as

$$\begin{aligned} G_E^{\Sigma^\pm}(Q^2) &= F_1^{\Sigma^\pm} - \tau_{\Sigma^\pm} F_2^{\Sigma^\pm} \\ &= F_1^{S*} + F_1^{V*} - \tau(F_2^{S*} + F_2^{V*}), \end{aligned} \quad (38)$$

$$G_M^{\Sigma^\pm}(Q^2) = F_1^{\Sigma^\pm} + F_2^{\Sigma^\pm} = F_1^{S*} + F_1^{V*} + F_2^{S*} + F_2^{V*}, \quad (39)$$

where $\tau_{\Sigma^\pm} = \frac{Q^2}{4M_{\Sigma^\pm}^2}$ and $M_{\Sigma^\pm}$ is the vacuum mass of the hyperon. The isoscalar and isovector form factors of $\Sigma^\pm$ can now be expressed as [70].

$$F_{1\Sigma^+}^{S*}(Q^2) = \frac{1}{2}g_1(Q^2) \left[(1 - \beta_\omega - \beta_\phi) + \beta_\omega \frac{(m_\omega^*)^2}{(m_\omega^*)^2 + Q^2} + \beta_\phi \frac{(m_\phi^*)^2}{(m_\phi^*)^2 + Q^2} \right], \quad (40)$$

$$F_{1\Sigma^+}^{V*}(Q^2) = \frac{1}{2}g_1(Q^2) \left[(1 - \beta_\rho) + \beta_\rho \frac{(m_\rho^*)^2}{(m_\rho^*)^2 + Q^2} \right], \quad (41)$$

$$F_{2\Sigma^+}^{S*}(Q^2) = \frac{1}{2}g_1(Q^2) \left[(2\mu_{\Sigma^+}^* - 2 - \alpha_\phi - \alpha_\rho) \frac{(m_\omega^*)^2}{(m_\omega^*)^2 + Q^2} + \alpha_\phi \frac{(m_\phi^*)^2}{(m_\phi^*)^2 + Q^2} \right], \quad (42)$$

$$F_{2\Sigma^+}^{V*}(Q^2) = \frac{1}{2}g_1(Q^2) \left[\alpha_\rho \frac{(m_\rho^*)^2}{(m_\rho^*)^2 + Q^2} \right], \quad (43)$$

$$F_{1\Sigma^-}^{S*}(Q^2) = \frac{1}{2}g_2(Q^2) \left[(-1 - \beta_\omega - \beta_\phi) + \beta_\omega \frac{(m_\omega^*)^2}{(m_\omega^*)^2 + Q^2} + \beta_\phi \frac{(m_\phi^*)^2}{(m_\phi^*)^2 + Q^2} \right], \quad (44)$$

$$F_{1\Sigma^-}^{V*}(Q^2) = \frac{1}{2}g_2(Q^2) \left[(-1 - \beta_\rho) + \beta_\rho \frac{(m_\rho^*)^2}{(m_\rho^*)^2 + Q^2} \right], \quad (45)$$

$$F_{2\Sigma^-}^{S*}(Q^2) = \frac{1}{2}g_2(Q^2) \left[(2\mu_{\Sigma^-}^* + 2 - \alpha_\phi - \alpha_\rho) \frac{(m_\omega^*)^2}{(m_\omega^*)^2 + Q^2} + \alpha_\phi \frac{(m_\phi^*)^2}{(m_\phi^*)^2 + Q^2} \right], \quad (46)$$

$$F_{2\Sigma^-}^{V*}(Q^2) = \frac{1}{2}g_2(Q^2) \left[\alpha_\rho \frac{(m_\rho^*)^2}{(m_\rho^*)^2 + Q^2} \right]. \quad (47)$$

The effective magnetic moment $\mu_{\Sigma^\pm}^*$ gives the total magnetic moment of the Σ hyperon calculated from the CQMF model, which includes contributions from valence, sea, and orbital quarks.

The EMFFs of the Λ hyperon gets contribution from the isoscalar channel only and are given as [37]

$$G_M^{\Lambda*} = F_{1\Lambda}^{S*} + F_{2\Lambda}^{S*} \quad \text{and} \quad G_E^{\Lambda*} = F_{1\Lambda}^{S*} - \tau_\Lambda F_{2\Lambda}^{S*},$$

where $\tau_\Lambda = Qn^2/4\mathcal{M}_\Lambda^2$ and $\mathcal{M}_\Lambda$ denotes vacuum mass of the Λ hyperon. Taking into account the isoscalar property of the Λ hyperon, the contribution of the ρ meson and its resonance states has been excluded. In this work, we have included the contributions from the resonance states [37]. Considering p-QCD and asymptotic behavior of the form factors and including the constraints leading to parametrized forms [71,72], we get the isoscalar Dirac and Pauli form factors for the Λ hyperon, which are, respectively, expressed as

$$F_{1\Lambda}^{S*}(Q^2) = \frac{g(Q^2)}{3} \sum_{i=1}^I \left[-b_{\omega_i} - b_{\phi_i} + b_{\omega_i} \frac{(m_{\omega_i}^*)^2}{(m_{\omega_i}^*)^2 + Q^2} + b_{\phi_i} \frac{(m_{\phi_i}^*)^2}{(m_{\phi_i}^*)^2 + Q^2} \right],$$

$$F_{2\Lambda}^{S*}(Q^2) = \frac{g(Q^2)}{3} \sum_{i=1}^I \left[(\mu_\Lambda^* - a_{\phi_i}) \frac{(m_{\omega_i}^*)^2}{(m_{\omega_i}^*)^2 + Q^2} + a_{\phi_i} \frac{(m_{\phi_i}^*)^2}{(m_{\phi_i}^*)^2 + Q^2} \right].$$

Here, $I = 3$ represents the number of resonance states, where ω_i ($i = 1, 2, 3$) correspond to the vector mesons $\omega(782)$, $\omega(1420)$, and $\omega(1650)$, while ϕ_i denote the vector mesons $\phi(1020)$, $\phi(1680)$, and $\phi(2170)$. The values of free parameters and coefficients used in the current study of the

TABLE II. Masses and widths of the vector mesons (in MeV) used in the calculation of the Sachs form factor of the Λ hyperon [37].

State	Mass	Width	State	Mass	Width
$\omega(782)$	782	8.1	$\phi(1020)$	1019	4.2
$\omega(1420)$	1418	104	$\phi(1680)$	1674	165
$\omega(1650)$	1679	121	$\phi(2170)$	2171	128

TABLE III. The parameter values used for the calculation of the Sachs form factors of the Λ hyperon [37,62].

Parameter	Value	Parameter	Value	Parameter	Value
$b_{\omega(782)}$	1.248	$b_{\omega(1420)}$	0.712	$b_{\omega(1650)}$	1.013
$b_{\phi(1020)}$	-1.902	$b_{\phi(1680)}$	-0.581	$b_{\phi(2170)}$	-0.584
$a_{\phi(1020)}$	-2.224	$a_{\phi(1680)}$	2.748	$a_{\phi(2170)}$	0.615

calculation of the Sachs form factor of the Λ hyperon are listed in Tables II and III.

III. RESULTS AND DISCUSSION

A. In-medium vector-meson masses

Using the CQMF model, we have minimized the thermodynamic potential Ω and obtained the in-medium values of the nonstrange isoscalar field σ , the strange scalar field ζ , scalar isovector field δ , and dilaton field χ . These field values have been used to calculate the quark and gluon condensates using Eqs. (8)–(11). The scalar gluon condensates of QCD are simulated by a scalar dilaton field χ . In the present model, the values of the quark masses are taken as $m_u = 4$, $m_d = 7$, and $m_s = 150$ MeV. In vacuum, using Eqs. (8)–(11) the value of condensate $(-m_q \langle \bar{q}q \rangle^{1/4})$ for u , d , and s quarks is found to be 95.88, 95.88, and 248.16 MeV, respectively, using Eqs. (8)–(11). (In vacuum scalar isovector field δ is 0). All three u , d , and s condensates $(-m_q \langle \bar{q}q \rangle^{1/4})$ decrease with increase in baryonic density. On the other hand, with the increase in isospin asymmetry, the u condensate increases and the d condensate decreases, which is clearly visible at higher baryonic density. For given isospin asymmetry and temperature of the nuclear matter, the scalar quark condensate is observed to decrease with increasing baryonic density. The NJL model [73] describes the feature of the spontaneous chiral symmetry breaking of QCD which gives nonzero values of the quark-antiquark condensates. In vacuum, the values of the scalar quark condensates $(\langle \bar{q}q \rangle)$ are obtained to be -276.40 , -229.51 , and -293.5 MeV³ for nonstrange u and d and strange s quarks, respectively, with $m_u \neq m_d$. The same quantities as obtained from the NJL model are -247.8 , -247.8 , and -258.3 MeV³, respectively, with $m_u = m_d$ [73]. In the QCD sum rule, the in-medium masses of the light vector mesons have been calculated and presented in Fig. 1(a) for the ρ meson (m_ρ^*), Fig. 1(b) for the ω meson (m_ω^*), and Fig. 1(c) for the ϕ meson (m_ϕ^*) as

a function of baryonic density ρ_B at different values of temperature T and isospin asymmetry η . Using the finite energy sum rules in vacuum, the value of the parameters k_u , k_d , and k_s appearing in Eqs. (19) and (20) are obtained as 3.59, 5.64, and -1.13 , respectively. For the ω meson, at $T = 0$ MeV, the effective mass obtained is 783.00 MeV. At $T = 100$ MeV, the effective mass is found to be 782.88 MeV. The in-medium mass further increases with increase in isospin asymmetry. The effective masses decrease by 15.46% and 41.69% as baryonic density changes from $\rho_B = 0$ to ρ_0 and $3\rho_0$, respectively. For the asymmetric medium $\eta = 0.3$, the values of m_ω^* at ρ_0 and $3\rho_0$ are observed to be 665.60 and 472.31 MeV, respectively. For the ρ meson, at vacuum, $T = 0$ and $T = 100$ MeV the effective masses are found to be 770.00 and 769.88 MeV, respectively. A visible effect of isospin asymmetry on m_ρ^* has been observed at both $T = 0$ and $T = 100$ MeV. For the ϕ meson, at vacuum $T = 0$ MeV, the effective mass is found to be 1020 MeV. The in-medium mass of the ϕ meson decreases with increase in baryonic density. A very slight variation with isospin asymmetry on the in-medium mass of the ϕ meson has been observed. The results obtained are consistent with the studies in Ref. [48].

B. Nucleon's Sachs electric and magnetic form factors

The variations of the nucleon's vacuum Sachs electric and Sachs magnetic form factors as function of Q^2 for $\eta = 0$ and $T = 0$ are shown in Fig. 2 and are also compared with the available experimental data [74,75]. The neutron's Sachs electric form factor results obtained aligns with the experimental data within error limits [76]. The calculated Sachs form factors of proton and Sachs magnetic form factor of neutron within the VMD framework are found to be in close agreement with lattice QCD results [75]. In Fig. 3, the vacuum Sachs form factors of the Σ hyperons have been compared with the results obtained from lattice QCD and our results aligns with those in Ref. [35].

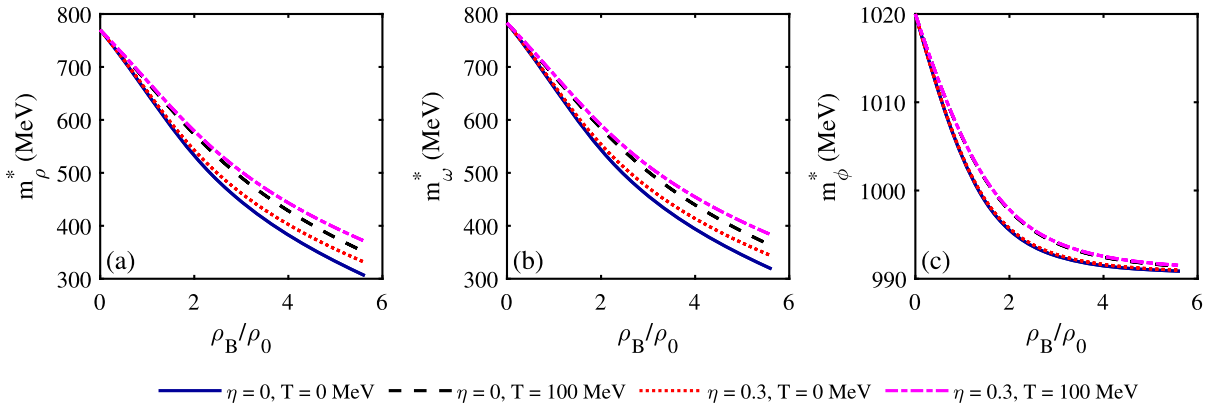


FIG. 1. Variation in the masses of the light vector mesons (a) ρ , (b) ω , (c) ϕ as a function of baryonic density ρ_B (in the units of ρ_0) at $T = 0$ and 100 MeV as well as with isospin asymmetry, $\eta = 0$ and 0.3.

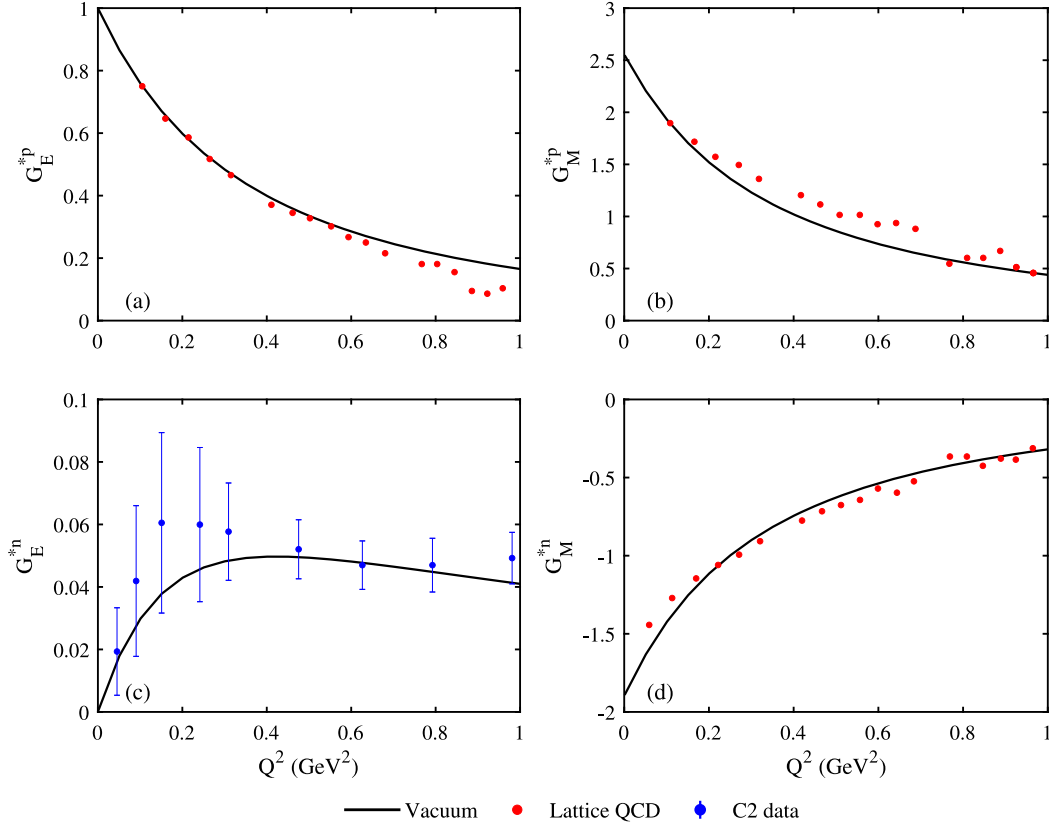


FIG. 2. The vacuum ($\rho_B = 0, \eta = 0, T = 0$ MeV) Sachs electric form factor $G_E^{*p,n}$ (a),(c) and Sachs magnetic form factor $G_M^{*p,n}$ (b),(d) of the baryons p, n are shown as a function of momentum transfer Q^2 (in GeV^2). Comparison has been made with the available experimental results for G_E^{*n} [76] and lattice QCD results for G_E^{*p} and $G_M^{*p,n}$ [75].

The Sachs electric form factor of the proton G_E^{*p} as a function of the Q^2 for different isospin asymmetry η and baryonic density ρ_B at $T = 0$ MeV are shown in Fig. 4(a). The values of the G_E^{*p} are observed to decrease monotonically with increasing Q^2 up to $Q^2 = 2-3$ and thereafter showing a saturation behavior. With increasing baryonic density ρ_B , the suppression of G_E^{*p} is further noticeable, reflecting the enhanced medium effects at higher densities. With increasing isospin asymmetry $\eta = 0.3$, a negligible change in G_E^{*p} is seen. In Fig. 4(b), the proton Sachs magnetic form factor exhibits a rapid monotonic decrease in the low momentum transfer region $0 \leq Q^2 \leq 2$. In the intermediate region $2 \leq Q^2 \leq 4$, the decrease becomes weaker on the considered scale, while for higher momentum transfers $Q^2 \geq 4$, the form factors show an almost constant behavior. An increase in the baryonic density from $\rho_B = 0$ to $3\rho_0$ leads to a systematic enhancement of the magnetic form factors over the entire range of Q^2 values. The presence of isospin asymmetry $\eta = 0.3$ has visible effect on these form factors. At finite temperature, only the magnitude of the form factors is noticeably affected, whereas the overall qualitative behavior remains unchanged.

In Fig. 4(c), the Sachs electric form factor of the neutron G_E^{*n} at $T = 0$ MeV shows a rapid rise in the low- Q^2 region and develops a pronounced maximum around $0.5 \leq Q^2 \leq 1.5$. The height of this peak shifts upward with increase in baryonic density ρ_B , with an enhancement of approximately 10%–20% relative to the vacuum case. The peak shifts toward higher Q^2 with increasing baryonic density ρ_B and negligible impact of isospin asymmetry η is observed. Beyond the peak, G_E^{*n} decreases monotonically with increasing Q^2 , and values start converging at higher momentum transfer. The enhancement of G_E^{*n} at low and intermediate values of Q^2 reflect the significant redistribution of the internal charge structure of the neutron in the dense matter, whereas the Sachs magnetic form factor of the neutron G_M^{*n} shows a monotonic increase with momentum transfer over the entire Q^2 range. G_M^{*n} rises rapidly in the low- Q^2 region in the range $0 \leq Q^2 \leq 1.5$. In the intermediate region, $1.5 \leq Q^2 \leq 4$, the rate of increase becomes slower, and for higher momentum transfers $Q^2 \geq 4$, G_M^{*n} nearly saturates, showing very weak Q^2 dependence. With increasing ρ_B and isospin asymmetry, there is a suppression of the G_M^{*n} over the entire Q^2 range, which has been depicted by the downward shift of the form factors.

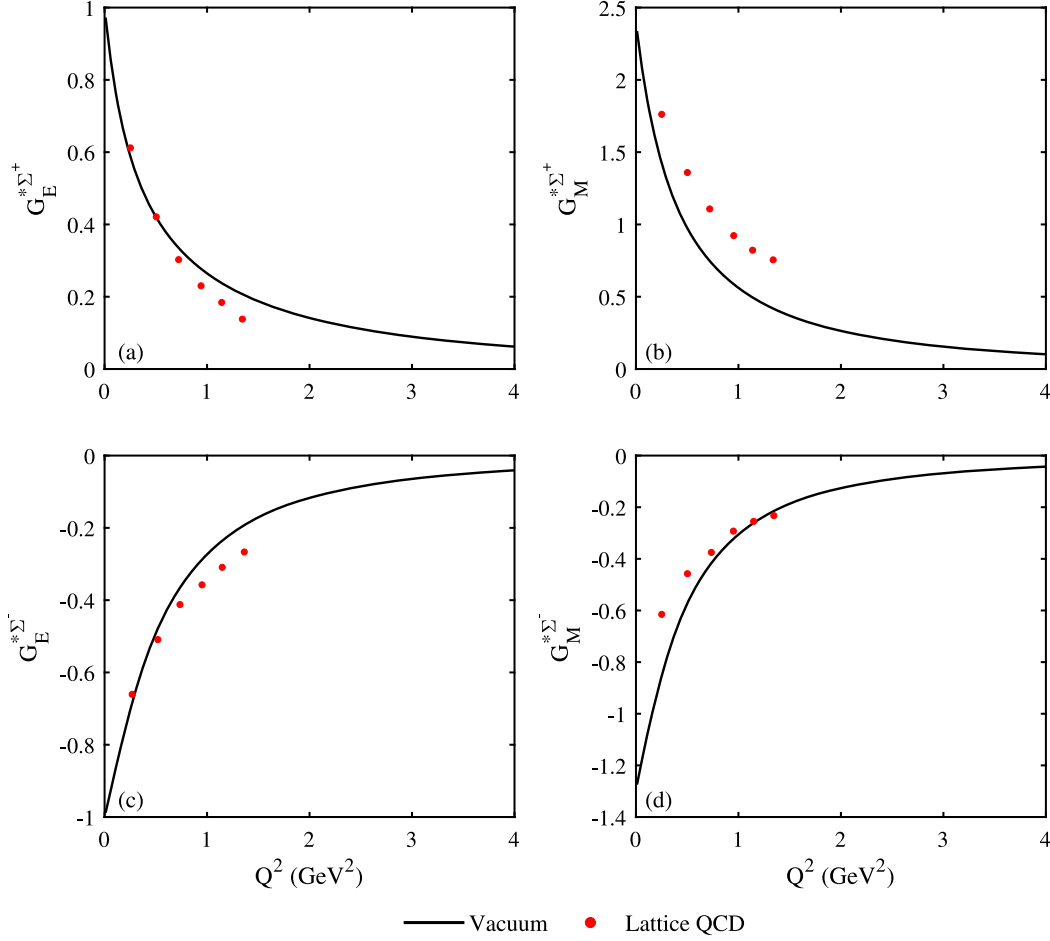


FIG. 3. The vacuum ($\rho_B = 0, \eta = 0, T = 0$ MeV) Sachs electric form factor $G_E^{*\Sigma^\pm}$ (a),(c) and Sachs magnetic form factor $G_M^{*\Sigma^\pm}$ (b),(d) of the $\Sigma^\pm$ hyperons are shown as a function of momentum transfer Q^2 (in GeV^2). Comparison has been made with the available lattice QCD results [70].

The temperature dependence of Sachs form factors for nucleons has been presented in Fig. 5. At finite temperature $T = 100$ MeV compared to the $T = 0$ MeV case, a further suppression of G_E^{*p} has been observed as shown in Fig. 5(a), with the effect more pronounced at higher baryonic density $3\rho_0$. In the proton's Sachs magnetic form factor, the temperature effect is slightly visible, mainly at low range of Q^2 , as presented in Fig. 5(b). The value of $G_E(0)$ for both proton and neutron is the same in-medium and vacuum because the charge is preserved in the medium. The trends in Sachs form factors of the neutron and Sachs electric form factor of the proton along with their variation with increasing ρ_B is found to be consistent with the results obtained from the covariant quark model [30,77]. In the current study of the Sachs magnetic form factor of the proton, G_M^{*p} shows enhancement with increasing baryonic density ρ_B and isospin asymmetry η . For the neutron's Sachs electric form factor, G_E^{*n} near the peak, a slight thermal enhancement is observed, and this effect becomes more visible at higher baryon density. For G_M^{*n} there is again slight thermal enhancement with temperature and a more

noticeable effect at larger baryonic densities in the low- Q^2 domain. Overall, a very small temperature dependence is visible at higher baryonic density on the form factors and their qualitative nature remains same.

Figure 6(a) shows the normalized in-medium proton's Sachs electric form factor at $T = 0$ MeV, having monotonic decrease with increasing momentum transfer Q^2 . The suppression in the value of the form factors increases with increasing in baryonic density ρ_B over the entire range of Q^2 values. The suppression is less at low momentum transfer $Q^2 \leq 1.5$ and becomes substantial at larger Q^2 . However, the strongest suppression is observed at $3\rho_0$ indicating substantial modification of the proton electric structure in a dense nuclear medium. With increasing isospin asymmetry η , there is a negligible deviation in the low- Q^2 range, whereas there is visible change at the high- Q^2 region, particularly at the high baryonic densities. The curves exhibit a monotonically decreasing trend that steepens with increasing baryonic density. This represents physical “swelling” of the bound proton arising due to interactions with mean scalar fields. Similar impact of η is

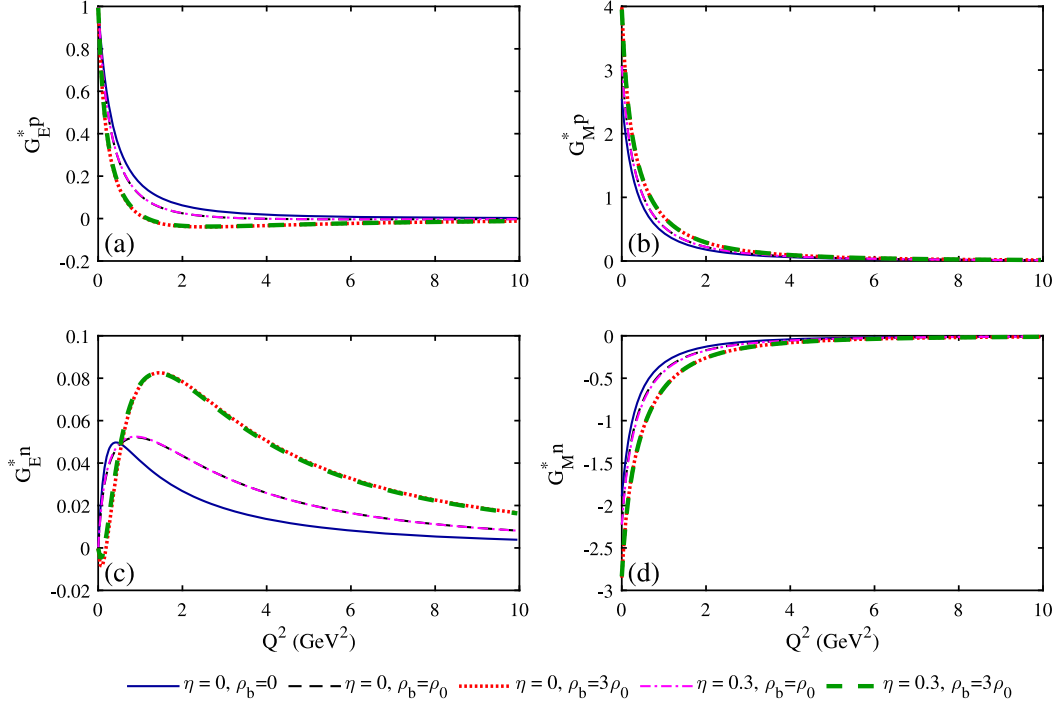


FIG. 4. The Sachs electric form factor $G_E^{*p,n}$ (a),(c) and Sachs magnetic form factor $G_M^{*p,n}$ (b),(d) for the baryons p, n are shown as a function of momentum transfer Q^2 (in GeV^2) for different values of baryonic density ρ_B and isospin asymmetry η at temperature $T = 0$ MeV.

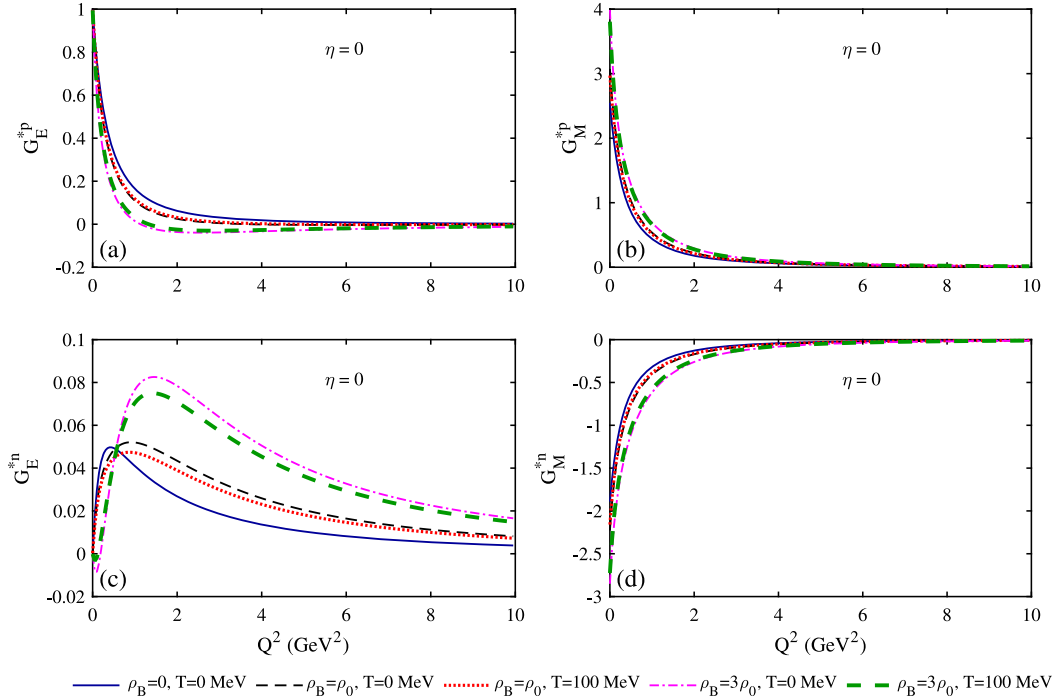


FIG. 5. Sachs electric form factor $G_E^{*p,n}$ (a),(c) and Sachs magnetic form factor $G_M^{*p,n}$ (b),(d) of the baryons p, n are shown as a function of Q^2 (in GeV^2) in symmetric nuclear medium ($\eta = 0$), at temperatures $T = 0$ and 100 MeV, as well as baryonic densities $\rho_B = 0, \rho_0$ and $3\rho_0$.

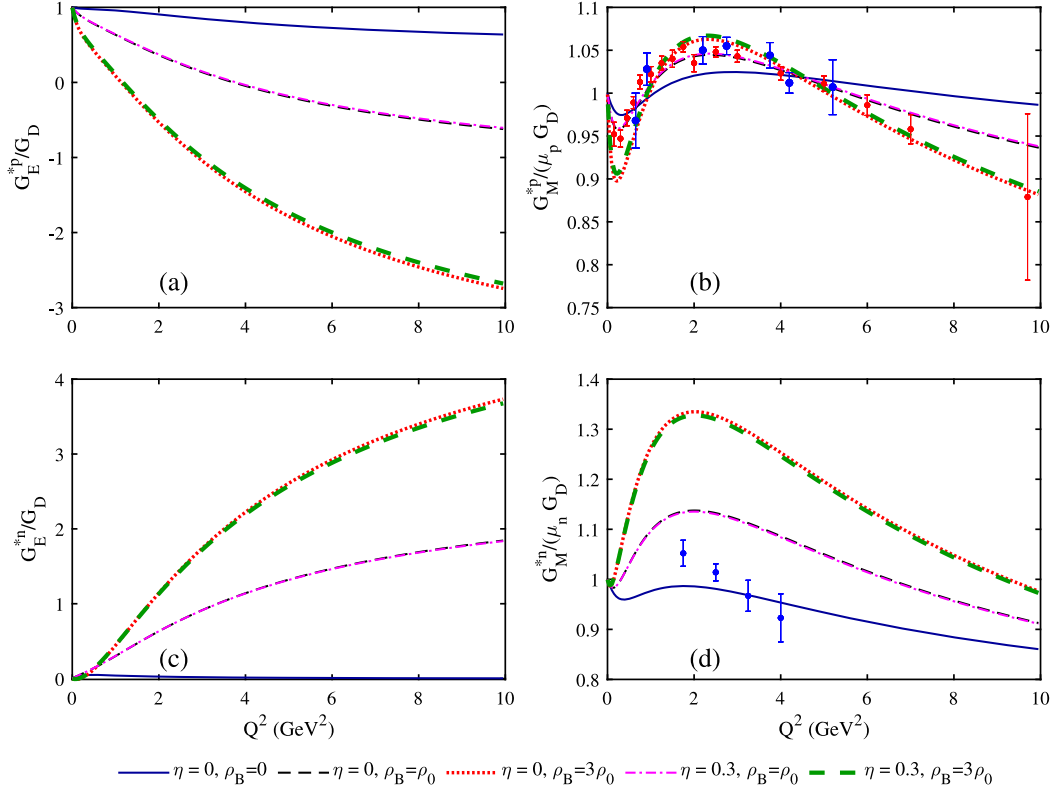


FIG. 6. Comparison of $G_E^{*p,n}/G_D$ (a),(c) and $G_M^{*p,n}/(\mu_{p,n}^* G_D)$ (b),(d) for the baryons p, n as a function of Q^2 (in GeV^2) for baryonic densities $\rho_B = 0, \rho_0$, and $3\rho_0$, as well as isospin asymmetry $\eta = 0, 0.3$ at temperature $T = 0$ MeV. The experimental data for the case of protons are shown by filled circles [78], whereas the remaining proton data are taken from Ref. [79]. The neutron magnetic form factor data are taken from Ref. [74].

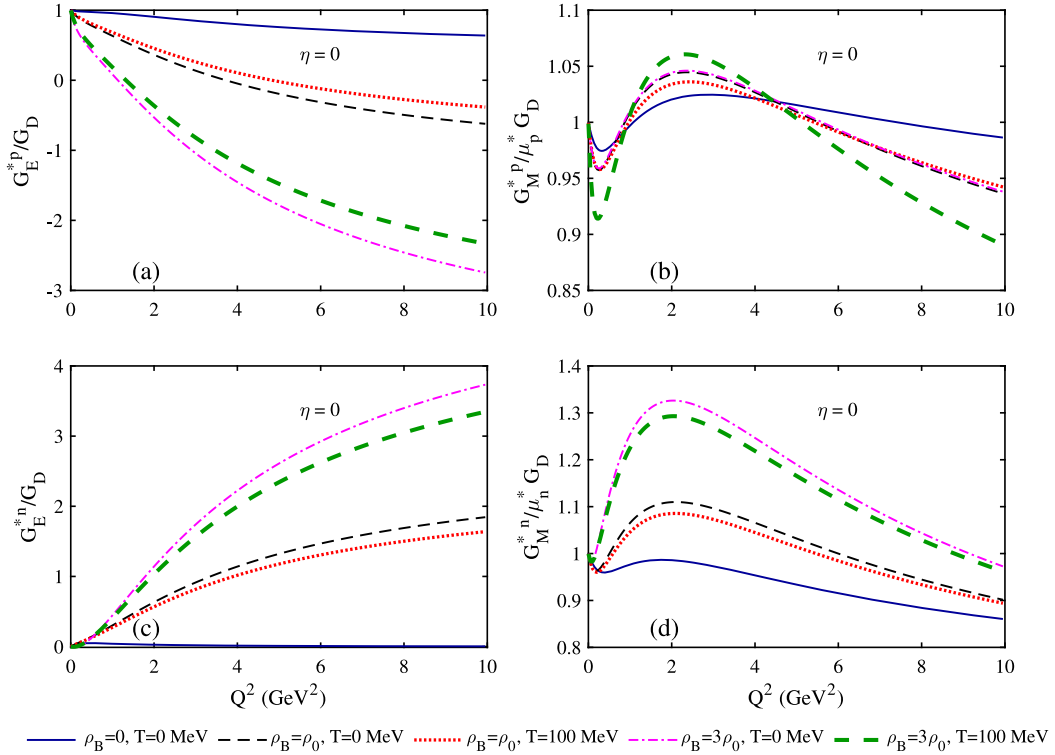


FIG. 7. Comparison of the Sachs electric form factor ratio $G_E^{*p,n}/G_D$ (a),(c) and Sachs magnetic form factor $G_M^{*p,n}/(\mu_{p,n}^* G_D)$ (b),(d) of the nucleon at $T = 0, 100$ MeV and baryonic densities $\rho_B = 0$ and $3\rho_0$.

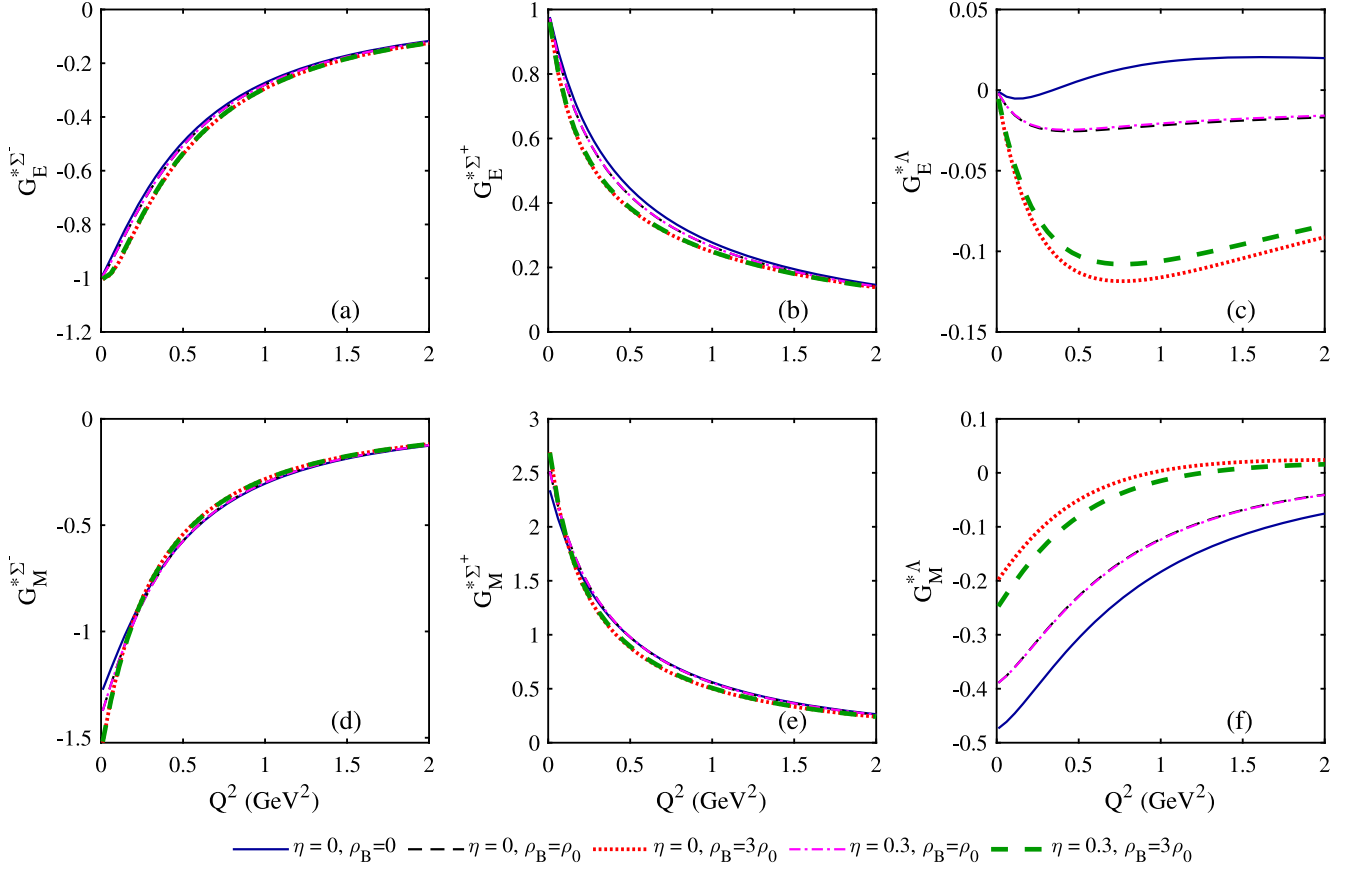


FIG. 8. Comparison of the Sachs electric form factors $G_E^{*\Sigma^-}$, $G_E^{*\Sigma^+}$, $G_E^{*\Lambda}$ [subplots (a)–(c)] and Sachs magnetic form factors $G_M^{*\Sigma^-}$, $G_M^{*\Sigma^+}$, $G_M^{*\Lambda}$ [subplots (d)–(f)] of the Σ^- , Σ^+ and Λ hyperons, are shown as a function of momentum transfer Q^2 (in GeV^2) at $T = 0$ MeV.

also observed for $G_M^{*p}/\mu_n G_D$ and G_E^{*n}/G_D ratios [Figs. 6(b) and 6(c), respectively]. The $G_M^{*p}/(\mu_p^* G_D)$ ratio in Fig. 6(b) depicts the effect of dense nuclear environment, modifying the meson cloud, thus enhancing the magnetic distribution relative to the dipole expectation. The G_E^{*n}/G_D in Fig. 6(c) starts at zero and reveals how strong scalar and vector fields polarize the bound neutron by pulling internal charge distributions. The $G_M^{*n}/(\mu_n^* G_D)$ in Fig. 6(d) depicts higher sensitivity to the nuclear medium, signifying profound alterations in internal spin-flavor dynamics. The temperature dependence of the normalized in-medium nucleon's Sachs form factors is shown in Fig. 7. The qualitative nature here remains the same with only a slight quantitative variation from the results obtained at $T = 0$ MeV.

C. $\Sigma^\pm$ and Λ hyperon's EMFFs

Figure 8 shows Sachs form factors of the hyperons $G_{E,M}^{*\Sigma^\pm}$ and $G_{E,M}^{*\Lambda}$ at $T = 0$ MeV. The magnitude of $G_E^{*\Sigma^+}$ decreases monotonically with increasing momentum transfer over the entire range $0 \leq Q^2 \leq 2$. Increase in baryonic density ρ_B leads to the suppression of Sachs electric form factors. The increase in η shows negligible impact as compared to the

effect of ρ_B on $G_E^{*\Sigma^+}$. In Fig. 8(a), for $G_E^{*\Sigma^-}$, the Sachs electric form factor decreases in magnitude as a function of Q^2 . These form factors suppresses with the increase in baryonic density. Increasing isospin asymmetry has negligible impact on these form factors. For example, as can be seen from Fig. 8(b), the maximum change occurs for $Q^2 \leq 1$ with suppression of about 10%–15% relative to the vacuum at $\rho_B = 3\rho_0$. The in-medium effects decrease with increasing Q^2 , whereas all curves tend to converge for $Q^2 \approx 2$. Figure 8(e) shows $G_M^{*\Sigma^+}$, which decreases monotonically with increasing Q^2 . The Sachs magnetic form factor suppresses with increase in the baryonic density and has negligible impact on the isospin asymmetry. The magnetic form factors, $G_M^{*\Sigma^-}$ at $T = 0$ MeV, are presented in Fig. 8(d) as a function of momentum transfer Q^2 , with magnitude initially suppressed below $Q^2 < 0.2$ then increasing rapidly in the Q^2 region $0.2 \leq Q^2 \leq 1.5$. The rate of increase is slower for $1.5 \leq Q^2 \leq 2$. Baryons containing a larger number of strange quarks tend to be less affected by medium modifications and the results obtained in the present work are similar to those as observed in Ref. [30]. For the Λ hyperon, Figs. 8(c) and 8(f) show the electric form

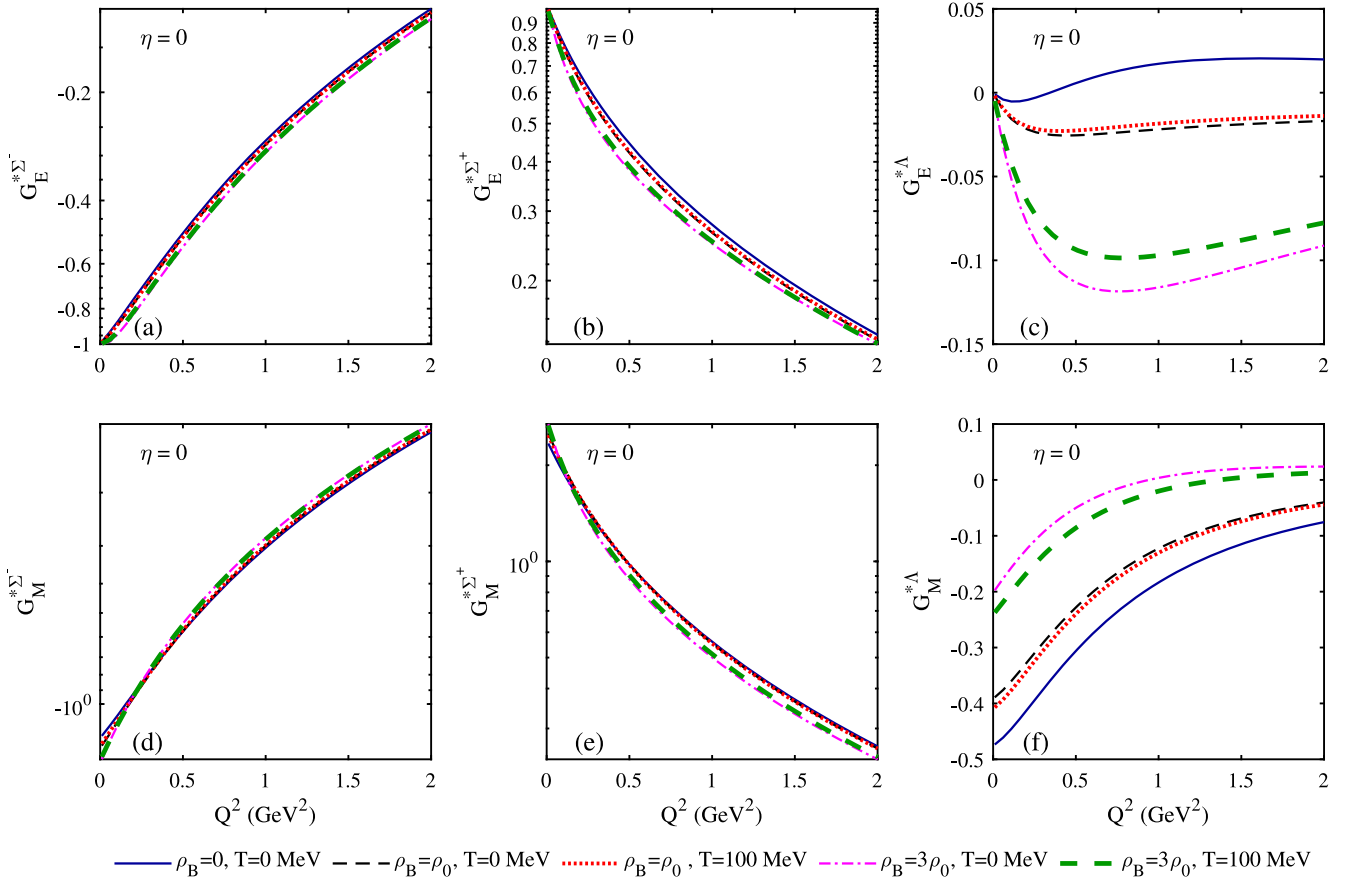


FIG. 9. Comparison of the Sachs electric form factors $G_E^{*\Sigma^-}$, $G_E^{*\Sigma^+}$, $G_E^{*\Lambda}$ [subplots (a)–(c)] and Sachs magnetic form factors $G_M^{*\Sigma^-}$, $G_M^{*\Sigma^+}$, $G_M^{*\Lambda}$ [subplots (d)–(f)] of the Σ^- , Σ^+ and Λ hyperons, shown as a function of momentum transfer Q^2 (in GeV^2) at $T = 0, 100$ MeV and at different baryonic densities ρ_B .

factor $G_E^{*\Lambda}$ and magnetic form factor $G_M^{*\Lambda}$, respectively. The $G_E^{*\Lambda}$ curves first decrease in magnitude, reach a minima, and then increase. The $G_M^{*\Lambda}$ increases with increase in Q^2 . There is visible change in form factors with increasing baryonic density and isospin asymmetry in both electric and magnetic form factors.

As shown in Fig. 9, Sachs electric and magnetic form factor of both $\Sigma^\pm$ shows very much less temperature sensitivity. The results for the hyperon's Sachs electric and magnetic form factors as a function of Q^2 show a good agreement with the results obtained in Refs. [30,80]. For the neutral hyperon Λ , the temperature dependence is relatively weaker for densities lower than $3\rho_0$, with clear deviations at higher densities as shown in Fig. 9(c) and comparatively less in case of Sachs magnetic form factors in Fig. 9(f). Overall, these results indicate that the influence of temperature is amplified in the dense nuclear medium.

D. Charge radii

In the present study, we have calculated the electric and magnetic charge radii of the baryons, which can be respectively expressed as

$$\langle r^2 \rangle_E = -6 \frac{dG_E(Q^2)}{dQ^2} \Big|_{Q^2=0}$$

and

$$\langle r^2 \rangle_M = -\frac{6}{\mu_b} \frac{dG_M(Q^2)}{dQ^2} \Big|_{Q^2=0}.$$

The values of electric and magnetic charge radii obtained from the current study have been summarized in Table IV and are compared with the experimental results [12,81]. The variations of the electric and magnetic charge radii as a function of baryonic density are presented in Figs. 10 and 11, respectively. We have observed that the electric and magnetic charge radii for the baryons increase with baryonic density as witnessed through the in-medium modification of the form factors. Increasing baryonic densities lead to redistribution of electric charge and magnetization in the nucleons, thus changing the internal structure in the dense nuclear matter. Figure 10 shows the electric and magnetic charge radii for the case of protons and neutrons. The charge radii are observed to increase with an increase in the baryonic density. For protons, the electric charge radius at $\rho_B = 0$ is 0.829 fm, which changes

TABLE IV. The electric and magnetic charge radii of the baryons are compared with the VMD model and available experimental data. The quantities $\langle r_E^{n2} \rangle$ and $\langle r_E^{\Sigma^{-2}} \rangle$ are in fm^2 , whereas for other baryons the results are in femtometers.

Baryon	Charge radii	Experimental value	VMD model	Current work		
				$\rho_B = 0$	$\rho_B = \rho_0/2$	$\rho_B = \rho_0$
p	$\langle r_E^{p2} \rangle^{1/2}$	0.862 ± 0.012 [82]	0.838 [47]	0.829	0.8698	0.9217
	$\langle r_M^{p2} \rangle^{1/2}$	0.855 ± 0.035 [3]	0.825 [47]	0.835	0.8517	0.8726
n	$\langle r_E^{n2} \rangle$	-0.115 ± 0.003 [83]	-0.100 [47]	-0.098	-0.0907	-0.0778
	$\langle r_M^{n2} \rangle^{1/2}$	0.873 ± 0.011 [2]	0.834 [47]	0.844	0.8487	0.8522
Λ	$\langle r_E^{\Lambda2} \rangle^{1/2}$	...	0.11 [37]	0.154	0.1844	0.2211
	$\langle r_M^{\Lambda2} \rangle^{1/2}$	...	0.42 [37]	0.294	0.3167	0.3462
Σ^+	$\langle r_E^{\Sigma^+2} \rangle^{1/2}$	...	...	0.561	0.6042	0.6616
	$\langle r_M^{\Sigma^+2} \rangle^{1/2}$	...	...	0.587	0.6307	0.6910
Σ^-	$\langle r_E^{\Sigma^-2} \rangle$	...	...	-0.275	-0.2375	-0.1865
	$\langle r_M^{\Sigma^-2} \rangle^{1/2}$	...	...	0.359	0.3862	0.4281

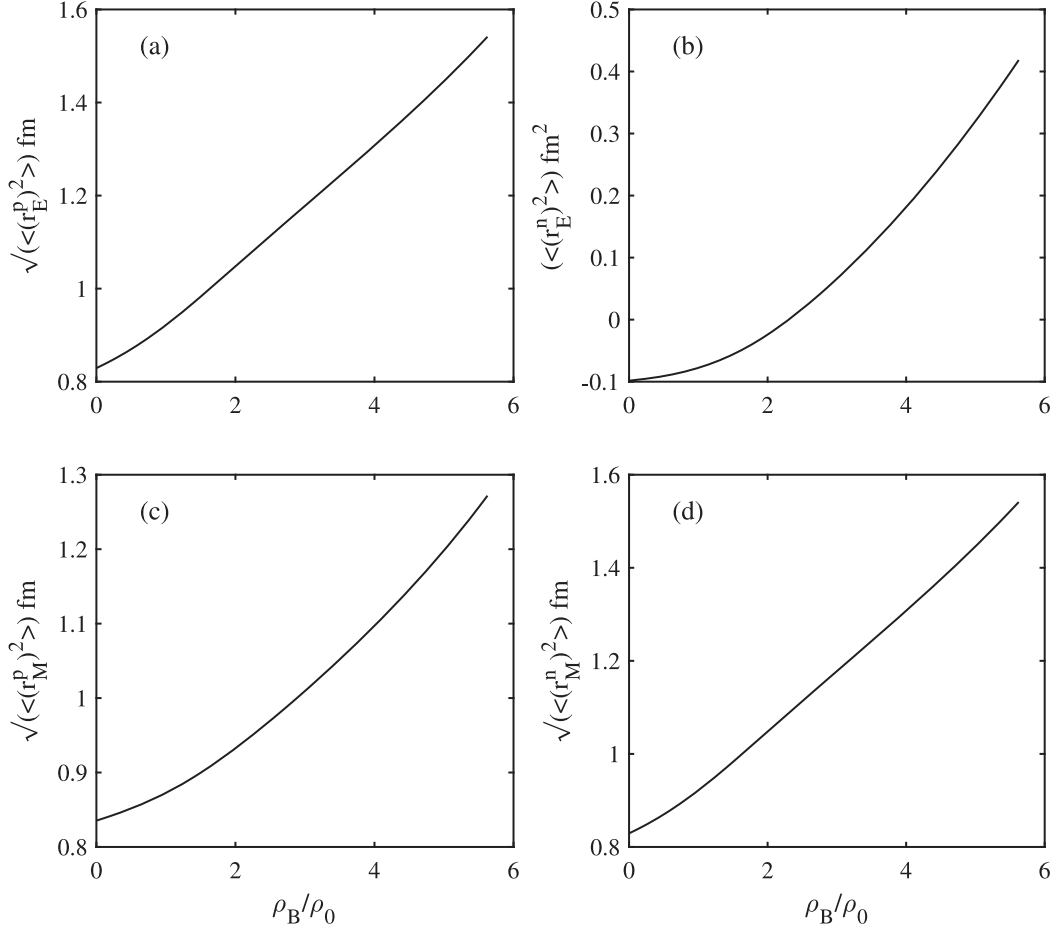


FIG. 10. Electric charge radii $\langle (r_E^p)^2 \rangle^{1/2}$, $\langle (r_E^n)^2 \rangle$ [subplots (a) and (b)] and magnetic charge radii $\langle (r_M^{p,n})^2 \rangle^{1/2}$ [subplots (c) and (d)] of the nucleons as a function of baryon density ρ_B (in units of ρ_0) at $T = 0$ MeV and $Q^2 = 0$.

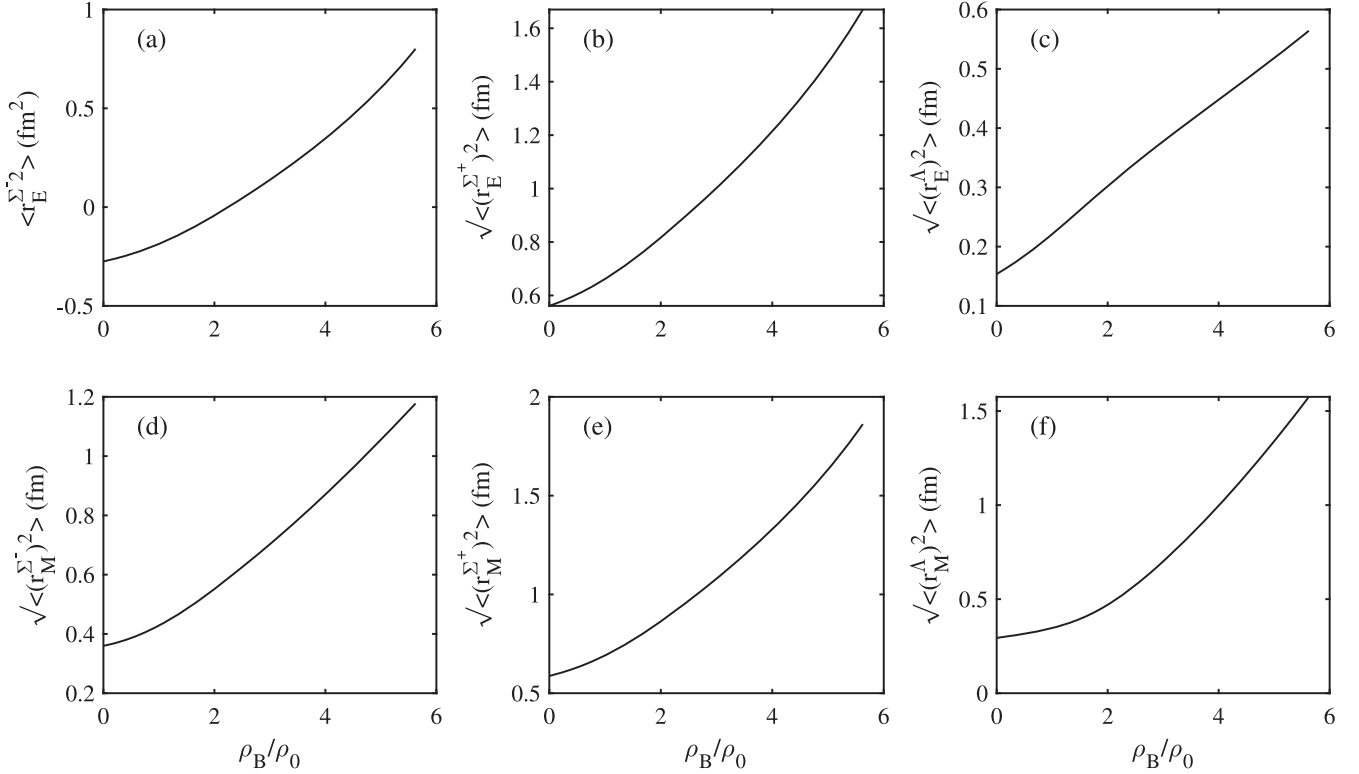


FIG. 11. Electric charge radii $\langle (r_E^{\Sigma^\pm})^2 \rangle$, $\langle (r_E^{\Sigma^\pm, \Lambda})^2 \rangle^{1/2}$ [subplots (a)–(c)] and magnetic charge radii $\langle (r_M^{\Sigma^\pm, \Lambda})^2 \rangle$ [subplots (d)–(f)] of the hyperons as a function of baryon density ρ_B (in units of ρ_0) at $T = 0$ MeV and $Q^2 = 0$.

to 0.922 fm at $\rho_B = \rho_0$ and 1.186 fm at $3\rho_0$. For protons, the magnetic charge radii value at $\rho_B = 0$ is found to be 0.832 fm, which changes to 0.876 and 1.015 fm at $\rho_B = \rho_0$ and $3\rho_0$, respectively. For neutrons, enhancement in the charge radii with baryonic density has been observed and is given in Table IV.

Figure 11 shows the electric and magnetic charge radii of the $\Sigma^\pm$ and Λ hyperons. For Σ^+ , the electric charge radius value at $\rho_B = 0$ is 0.561 fm and changes to 0.6616 and 1.0023 fm at $\rho_B = \rho_0$ and $3\rho_0$, respectively. The magnetic charge radius of Σ^+ at $\rho_B = 0$ is 0.587 fm and changes to 0.691 and 1.079 fm at $\rho_B = \rho_0$ and $3\rho_0$, respectively. An increase has been observed in the charge radii with the baryonic density for Σ^- and Λ hyperons and are presented in Table IV.

The vacuum values obtained are consistent with the experimental and other theoretical models [2,3,37,47,81–83].

IV. SUMMARY

To summarize, in the current study, the quark and gluon condensates have been investigated in the CQMF model, which are further taken as inputs to calculate the effective masses of the light vector mesons using the QCD sum rule approach. The dependence of masses of the light vector mesons on the baryonic density has been studied and the masses are found to decrease with increase in baryonic

density. The introduction of isospin asymmetry in the medium is observed to cause splitting in the corresponding quarks and quark condensates and hence in the in-medium meson masses. Isospin asymmetry effects are observed to be more dominant for the mesons composed of the light u and d quarks, whereas the strangeness effect becomes less noticeable for the mesons having strange quarks due to its weak interaction with the nuclear matter.

The Dirac and Pauli form factors of the baryons calculated within the framework of the VMD model are dependent on the effective masses of the vector mesons under consideration, which are then used to calculate the Sachs form factors, dipole ratios, and charge radii of the baryons. The Sachs form factors shows an appreciable dependence on baryonic density, but slight dependence on temperature and isospin asymmetry. The modification of Sachs form factors in the nuclear matter varies from one baryon to another and depends on the baryon's properties differently. The charge radii at vacuum are found close to the experimental values. The electric and magnetic charge radii of the baryons are found to increase with increasing baryonic density.

The calculations at higher baryonic densities are important as they can be used for studies with the astrophysical implications. Higher density (up to $\rho_B = 3\rho_0$) represents neutron-star core density where possible exotic phases and dense matter effects become significant. The present study

of the in-medium form factors of the baryons will be useful for future experimental facilities like EIC. The current work can be extended to obtain the density-dependent EMFFs in the timelike region.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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