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The holographic paradigm of hadron dynamics for medium modified nuclear matters

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ABSTRACT

We propose a medium-modified holographic-hadron dynamics suitable for the study of symmetric nuclear matter, with a key property of a simple law for the evolution of the five dimensional mass with the scalar background field. We show that the model satisfies symmetric nuclear matter constraints, namely, incompressibility and density dependence of the pressure, with only three free adjustable parameters fitted to the free nucleon mass and the nuclear matter saturation properties. We found that the holographic nucleon swells and the UV behavior of the associated string amplitude is damped, with the scaling property at short distances softened. Both effects can also generate observable consequences reflecting an average leakage of partons to the nuclear medium when density is increased, in the route towards the deconfinement of the internal nucleon degrees of freedom.

1. Introduction

It is expected that QCD confinement, still not fully understood, should breakdown at high densities in a nuclear matter environment by the action of the medium on the hadron constituents. That could eventually happen in the core of compact stars, which can attain densities few times larger than the normal nuclear density. The signature of the quark-gluon plasma was observed in relativistic heavy ion collisions in the LHC [1], where the matter is compacted at high temperatures in the initial stages of the heavy ion reaction.

The manifestation of the deconfinement dynamics can appear not in a dramatic fashion as in the heavy-ion collisions or in the core of compact starts but slowly driven by the increase of the nuclear matter density. Lattice QCD have not yet been able to provide results at finite density, with real chemical potentials[2]. Therefore one has to resort at present to models of hadrons in a medium. The quark-meson coupling model (QMC) proposed many years ago by Guichon [3] and independently by Frederico et al. [4,5] in a modified version (MQMC), gives a tool to interfere the quarks confined in the nucleon with the surrounding nuclear environment by coupling the meson fields directly to the quarks, in a generalization of the $\sigma - \omega$ Walecka model [6]. The main effect is to decrease the constituent quark mass by the attractive scalar field, while the vector field just shift the quark energy, and the nucleon radius increase. The increase of the nucleon size also damps the nucleon scalar coupling constant with density implying that the effective nucleon mass decrease much less than the one in the standard Walecka model. That results in a softening of the EOS when the energy and density at the nuclear matter (NM) saturation point are fitted, with the corresponding decrease in the incompressibility at the nuclear saturation density towards the range of accepted values (see [7,8]). A recent achievement of the application of QMC to finite nuclei by Stone et al. [9] has demonstrated that the obtained energy density functional (EDF) is able to predict properties of even-even nuclei across the nuclear chart with only four parameters on a level comparable with the Skyrme EDF [10] which has a large set of parameters and systematically tested for symmetric and asymmetric NM in [8].

The hadron properties in QMC/MQMC models are changed only by the swelling of the quark state, while the ultraviolet behavior which in QCD is determined by the number of partons, spin and angular momentum content of the valence wave function [11] is unchanged. However, if the hadron start to leak out its partonic constituents due to the proximity to other nucleons, there is a non-zero probability that the asymptotic behavior of the nucleon explored with short wavelength probe changes in such a way that the transverse momentum distribution of the quark decreases slowly with respect to the free nucleon one. Although the dissolution of the nucleon by increasing the nuclear density seems natural, so far there is not any approach that: (i) provides the same

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quality for the EOS of nuclear matter as the successful QMC/MQMC models; and (ii) embodies the leakage of partons by increasing density.

The goal of this paper is to show that it is possible to build a model that satisfies (i) and (ii) within the AdS/QCD paradigm for medium modified nucleons. Our model satisfies the saturation properties and the constraints related to the density dependence of the thermodynamical pressure in symmetric NM [12,13]. For that aim, the AdS/QCD action (see [14–19]) of the nucleon is extended to include the scalar and vector background fields with a metric model proposed in [14] giving in the vacuum the Regge trajectories for the nucleon spectrum. Both the AdS in the ultraviolet region and the color-confinement in the infrared region are brought in the model. While there are recent works analyzing the medium modification of hadron properties within holographic perspectives [20–24], they do not address the nuclear matter equation of state. Here, we use a deformed AdS metric reproducing the Regge trajectories of the nucleon and delta excited states [14] with a modified 5d mass, as we discuss in the following.

2. Nucleon holographic model in nuclear matter

Our ansatz for the AdS/QCD action for a nucleon interacting with the scalar and vector fields is

$$S_\psi = \int d^4x dz\, \sqrt{g}\, e^{-\varphi(z)} \times \overline{\Psi}(x,z)\left\{i\Gamma^M \left(D_M + g_\omega\, \omega_M\right) - m_5^*\right\}\Psi(x,z)\,, \tag{1}$$

where $\Psi(x,z)$ is the fermion field and m_5^* is the effective 5-dimensional mass depending on the background nuclear scalar field σ. The background nuclear vector field is ω_M and g_ω is the coupling constant. This action provides the internal dynamics for the nucleon and its response to the nuclear medium. The key ingredient for the nucleon model in matter is the five dimensional mass dependence on σ denoted by the medium modified value m_5^*. The dilaton field φ is irrelevant for the fermion field dynamics as it factorizes in the equation of motion. The choice of UV AdS metric carrying also the IR confinement is discussed below, while all other quantities in the action are defined in Appendix A.

It is well known that the Witten's relation [25] between the product of the five dimensional mass and the AdS radius, namely, m_5R, is determined by the UV scaling behavior of the matrix element of the nucleon interpolation operator given by the twist dimension of the nucleon wave function at short distance, i.e. $m_5R = \tau - 2 = 1$, which is extended to the nuclear medium to obtain the medium modified nucleon mass and wave function. The idea is to modify the mass term of the AdS action, which is the main point in building the model paradigm in order to obtain the response of the nucleon to the nuclear medium. In our approach, the nuclear medium creates a scalar and vector mean fields, which have as sources the scalar and vector nucleon densities, as in the case of hadronic models [6] and also in the quark-meson coupling type models [3,4]. Such long range (or IR physics) represented by the scalar and vector mean fields are brought to the internal nucleon degrees of freedom by the coupling of the corresponding fields to the fermionic one in the 5d action. In the particular case of the scalar field, its coupling to the fermion changes the 5d mass.

In the soft wall model [26], the inclusion of the IR physics associated with confinement is brought by the dilaton field, which produces a reasonable meson spectrum in the heavy-light and heavy quarkonia cases [17]. This procedure is not effective in the fermionic case because the dilaton field is removed when the fermion field is rescaled [14]. The solution given in [18] was to change the IR physics by including the dilaton field directly together with the m_5 in the 5d fermionic action. Following the path of such framework, we incorporate the medium effects in the 5d action through the coupling between the fermion and scalar background field induced by the medium. This coupling naturally modifies m_5 bringing the effect of the long-range physics that represents the medium background. The vector mean field only gives a trivial shift in the nucleon energy.

Therefore, we propose that m_5^*R gets modified from the vacuum value still keeping a positive value $0 < m_5^*R < 1$ depending on the degree of medium modification represented by the mean scalar field strength. When the mean scalar field overwhelms the bare nucleon, the effective twist of system gets significantly modified from the free nucleon twist due to the interaction with the scalar field. The reaction of the nucleon to the density increase is to lose partons. We suggest that the depletion of the effective 5d mass with the scalar field is proportional to the m_5^* itself, meaning that more partons exist inside the hadron higher is the probability to lose them to the medium. This leads to a simple evolution equation:

$$\frac{d}{d\sigma}m_5^* = -\frac{m_5^*}{\sigma_0}\,, \tag{2}$$

where the scale σ_0 represents a typical NM value. This scale σ_0 will be fitted to the properties of the equation of state of the symmetric NM later on. The solution of Eq. (2) yields a nonlinear effective 5d mass dependence on the scalar field given by:

$$m_5^* = m_5\, e^{-\frac{\sigma}{\sigma_0}}\,, \tag{3}$$

and this formula implements the effective nucleon twist decrease with density mentioned previously. In the limit of small density, it expands as

$$m_5^* = m_5 - g_\sigma \sigma + \ldots . \tag{4}$$

where $g_\sigma = m_5/\sigma_0$ is interpreted as the quark-sigma coupling constant. For increasing densities up to $\sim 50\rho_0$, we found that $\sigma \sim \sigma_0$ in our parametrization of the nuclear matter saturation point. This point will be further discussed when presenting our results of the EOS. The formula (4) corresponds to the coupling of the fermion to the background nuclear scalar field.

In this study, the metric ansatz brings both UV conformal invariance and IR confinement as proposed in Ref. [14] assuming that the medium modification is slower than the change in the 5d mass. The metric and warp factor are respectively given by

$$g_{\mu\nu} = e^{-2A(z)}\eta_{\mu\nu} \text{ and } A(z) = -\log\left(\frac{R}{z} + \frac{\lambda^2 z}{R}\right)\,, \tag{5}$$

where $\eta_{\mu\nu}$ is the Minkowski metric. This metric model is able to reproduce the Regge trajectory of the nucleon and delta excited states as already shown [14]. We remind that the IR modified metric (5) has the same fermion equation of motion as the one obtained from the action given in [14], where the metric is AdS and m_5 in the IR region contains a quadratic dependence on z. This suggests that the 5d mass can incorporate physics beyond the twist, as we are proposing here, to include the nuclear medium modification in the action.

It may be reasonable to think that also the metric at some high matter density starts to be modified, as one would expect that even the source of confinement expressed by the metric vanishes. However, we assume that the NM affects the 5d mass and disregard the evolution of the metric with respect to the medium in our approach as its evolution appears much slower than the 5d mass evolution. Despite we have not considered the medium modification of the metric, the nucleon properties is changed by the nuclear density due to the damping of the effective potential for the Sturm-Liouville eigenvalue equation for its squared mass, as we show in the following.

3. Solution of the medium modified nucleon eigenvalue equation

The least action principle leads to the equation of motion for the nucleon field assuming the medium modified action, Eq. (1). Our ansatz for the 5d mass dependence on the scalar background field, Eq. (3), introduces a dependence with the background scalar field obtained with the infrared modified AdS/QCD metric, Eq. (5), in the effective potential for the nucleon square mass eigenvalue equation. In this way, the solution of the eigenvalue equation provides the nucleon effective mass M^* and the nucleon wave function in the nuclear medium. The NM is isotropic and the isoscalar vector field has only the time component nonzero, as the vector components vanishes. We use the notation $\omega^0 \equiv \omega$.

The eigenvalue equation for nucleon field is derived from the action (1) by redefining the fermionic fields as

$$\Psi(x,z) = e^{\varphi(z)/2}\psi(x,z), \tag{6}$$

then the string modes dual to the nucleon is decomposed into the left and right hand components

$$\psi(x,z) = \left[\frac{1+\gamma^5}{2}F_+(z) + \frac{1-\gamma^5}{2}F_-(z)\right]\psi_4(x), \tag{7}$$

where $\psi_4(x)$ satisfies the 4d Dirac equation $\left(i\gamma^i\partial_i - M^*\right)\psi_4(x) = 0$.

To cast the eigenvalue equation into a Sturm-Liouville form, we change the variables

$$F_\pm(z) = e^{2A(z)} f_\pm(z), \tag{8}$$

and in terms of the reduced string amplitudes the equations of motion become:

$$-f''_\pm(z) + V^*_\psi f_\pm(z) = (E^* + g_\omega\,\omega)^2 f_\pm(z), \tag{9}$$

where the medium modified effective potential is

$$V^*_\psi = m^*_5 e^{-A(z)}\left(m^*_5 e^{-A(z)} \mp A'(z)\right). \tag{10}$$

For zero baryonic density V^*_ψ is the vacuum potential V_ψ, which is:

$$V_\psi(z) = m_5 R\,\frac{(m_5 R \mp 1)}{z^2} + \lambda^2\frac{m_5}{R}(2m_5 R \pm 1) + \lambda^4\frac{m_5^2}{R^2}z^2. \tag{11}$$

Inserting the warp factor (5) in the general form given by Eq. (10) one obtains the detail form of the medium modified potential:

$$\begin{aligned} V^*_\psi(z) = {} & m_5 R\, e^{-\frac{\sigma}{\sigma_0}}\,\frac{(m_5 R\, e^{-\frac{\sigma}{\sigma_0}} \mp 1)}{z^2} \\ & + \lambda^2\frac{m_5}{R}\,e^{-\frac{\sigma}{\sigma_0}}(2m_5 R\, e^{-\frac{\sigma}{\sigma_0}} \pm 1) \\ & + \lambda^4\frac{m_5^2}{R^2}\,e^{-2\frac{\sigma}{\sigma_0}}z^2, \end{aligned} \tag{12}$$

where both the strength of the UV conformal potential and the harmonic confinement are damped by increasing the scalar background field. Two effects are expected in the nucleon state: (i) it swells growing in size due to the decrease in the strength of the harmonic potential, and (ii) the asymptotic wave function in the UV region will have a smaller power for the scaling behavior as $z \to 0$ and correspondingly at large transverse momentum it will decrease slower than the vacuum wave function, reflecting an average leakage of partons to the nuclear medium.

The mass spectrum for the nucleon and its excited states is analytical for the given metric and is the solution of the eigenvalue equation (9):

$$\begin{aligned} (E^*_n + g_\omega\,\omega)^2 = {} & 4\frac{\lambda^2}{R^2}m_5 R\,\exp(-\sigma/\sigma_0) \\ & \times\left(n + m_5 R\,\exp(-\sigma/\sigma_0) + \frac{1}{2}\right), \end{aligned} \tag{13}$$

where the slope of the Regge trajectory diminishes with the increase of the background field. The separation of the radial states of the nucleon inside the nuclear medium decreases as the slope of the Regge trajectory goes down with the background scalar field.

The nucleon is the ground state of the medium modified eigenvalue equation and its energy is given by Eq. (13) for $(n=0)$:

$$E^*_0 \equiv E^*_N = -g_\omega\,\omega + M^*_N(\sigma), \tag{14}$$

where the nucleon effective mass is

$$M^*_N = 2\frac{\lambda}{R}\sqrt{m_5 R\, e^{-\frac{\sigma}{\sigma_0}}\left(m_5 R\, e^{-\frac{\sigma}{\sigma_0}} + \frac{1}{2}\right)}. \tag{15}$$

The key ingredient for building the nuclear matter model is the nucleon density dependent scalar coupling constant, given by the derivative of the nucleon medium modified mass (see e.g. [27]):

$$g_\sigma(\sigma) = -\frac{\partial}{\partial\sigma}M^*_N = \frac{\lambda m_5}{2\sigma_0}\,\frac{e^{-\frac{\sigma}{\sigma_0}} + 4m_5 R\, e^{-2\frac{\sigma}{\sigma_0}}}{\sqrt{m_5 R\, e^{-\frac{\sigma}{\sigma_0}}\left(m_5 R\, e^{-\frac{\sigma}{\sigma_0}} + \frac{1}{2}\right)}}. \tag{16}$$

The back-reaction to the nuclear medium of the nucleon is a depletion of $g_\sigma(\sigma)$, which is evident from the above equation when the background field σ gets its value in matter. The medium range attraction between the scalar exchange nucleons is softened in nuclear matter, which is the relevant effect for the nuclear matter EOS in QMC/MQMC models [3,4].

4. Nuclear matter EOS

We find that the AdS/QCD provides a new paradigm for the nucleon medium modification and the back-reaction to the nuclear matter equation of state, which provides a different scenario for the nuclear dynamics when compared to both QHD (Quantum Hadrodynamics) and QMC/MQMC models. In the simplest version of QHD, a structureless point like nucleon is interacting with the ambient scalar and vector fields, and coupling constants are independent of the nuclear density, while more sophisticated versions of QHD includes also derivative couplings to the fields, like the Zimanyi-Moszkowski model [28] and its generalizations (see e.g. [29] and the recent review [30] for applications in compact stars). In the QMC model, massless quarks inside the nucleon interacting with the ambient scalar and vector fields (with the help of self-consistent condition in QMC based on the bag boundary condition).

As a reference, we are going to compare two different coupling schemes of the scalar field with the nucleon within the $\sigma-\omega$ version of QHD, namely, the linear Walecka model [6], and within a medium modified holographic paradigm of hadron dynamics (MHD) applied to nuclear matter. In the first case of QHD, the coupling between the nucleon and the scalar field, g_σ is independent of the field and consequently of the nuclear density, while for MHD g_σ depends on the scalar field, i.e. $g_\sigma = g_\sigma(\sigma)$ as derived in Eq. (16), and therefore it contributes to the self-consistent gap equation for σ, bringing to it a nuclear density dependence. That also happens in the QMC/MQMC models, with the difference that now the scalar field affects both the short-distance behavior, namely, the power law behavior of the string amplitude, as well the large distances, where the soft-wall confinement is acting, and its effects is damped by increasing the density. The depletion of the confining interaction can be appreciated in the medium modified effective string potential of Eq. (12), where for $\sigma \gg \sigma_0$ one has that $V^*_\psi(z) \to 0$, which leads to continuum eigenvalues in the Sturm-Liouville equation, representing the situation where colors tend to be unconfined in the nuclear environment at extreme densities.

5. Summary of QHD equations

Medium-modified nucleon mass in QHD, or effective nucleon mass, is given by $M^*_N = M_N - g_\sigma\sigma = M_N - G^2_\sigma \rho_s$, since the field equation for σ is written as

$$\sigma = \frac{g_\sigma}{m^2_\sigma}\rho_s, \tag{17}$$

where g_σ is redefined by $m_\sigma\, G_\sigma$. Here one has a constant scalar coupling g_σ between the nucleon and the scalar field σ, and ρ_s is the scalar density. For the linear Walecka model, energy density and pressure are given, respectively, by [6]

$$\mathcal{E} = \frac{G^2_\omega}{2}\rho^2 + \frac{1}{2}m^2_\sigma\sigma^2 + \frac{\gamma}{2\pi^2}\int_0^{k_F} dk\, k^2(k^2 + M^{*2}_N)^{1/2} \tag{18}$$

and

$$P = \frac{G^2_\omega}{2}\rho^2 - \frac{1}{2}m^2_\sigma\sigma^2 + \frac{\gamma}{6\pi^2}\int_0^{k_F} dk\, \frac{k^4}{(k^2 + M^{*2}_N)^{1/2}}, \tag{19}$$

where k_F is the Fermi momentum, and γ is the degeneracy factor ($\gamma = 4$ for symmetric nuclear matter). The nuclear density is given by $\rho = (\gamma/6\pi^2)k^3_F$, and the coupling constants of the model are $G_\sigma = g_\sigma/m_\sigma$ and $G_\omega = g_\omega/m_\omega$, with m_σ and m_ω being the mass of the mesons σ and ω, respectively. The scalar field σ in the above equations can be written in terms of M^*_N through $\sigma = (M_N - M^*_N)/g_\sigma$.

For a given density, the effective nucleon mass is calculated from the so called gap equation as follows,

$$M^*_N = M_N - G^2_\sigma\rho_s = M_N - \frac{\gamma M^*_N G^2_\sigma}{2\pi^2}\int_0^{k_F} dk \frac{k^2}{(k^2 + M^{*2}_N)^{1/2}}. \tag{20}$$

Finally, the free parameters G^2_σ and G^2_ω are determined by imposing to the model a saturation point at $\rho = \rho_0$ with a binding energy given by B_0.

From Eqs. (18)-(19) it is possible to obtain all other thermodynamical quantities of the model. For instance, the incompressibility is found from Eq. (19) as

$$K = 9\frac{\partial P}{\partial \rho}. \tag{21}$$

For the linear Walecka model named as LHS [31] in which $\rho_0 = 0.15$ fm^{-3} and $B_0 = -15.8$ MeV, one find $K_0 \equiv K(\rho_0) = 548$ MeV, a very high value in comparison with recent analysis regarding this quantity, namely, $250\,\text{MeV} \leqslant K_0 \leqslant 315\,\text{MeV}$ [32].

6. Medium-modified holographic-hadron dynamics (MHD)

The medium modified holographic-hadron dynamics (MHD) presented here provides the non-linear σ-dependent nucleon mass $M^*_N(\sigma)$ given by Eq. (15) and the σ-dependent scalar coupling $g_\sigma(\sigma)$ given by Eq. (16). In contrast to QHD, the nontrivial σ-dependence of the scalar coupling is associated with the response to the external field of the nucleon internal degrees of freedom in MHD. In particular, the nuclear matter stability condition, i.e. $\frac{\partial\mathcal{E}}{\partial\sigma} = 0$, gives the mean field equation

$$\sigma = \frac{g_\sigma(\sigma)}{m^2_\sigma}\rho_s, \tag{22}$$

with ρ_s defined as in Eq. (20). Note here that Eq. (22) becomes Eq. (17) if $g_\sigma(\sigma)$ is taken as a constant. The energy density and pressure have the same functional form as those presented by the linear Walecka model, namely, Eq. (18) and Eq. (19).

We choose the following quantities and observables in order to obtain the unknown MHD parameters to build the equation of state of symmetric nuclear matter (SNM): $M_N = 939$ MeV (nucleon rest mass), $m_\sigma = 550$ MeV (σ meson mass), $m_5 R = 1$ (5d mass), $\rho_0 = 0.15$ fm^{-3} (saturation density) and $B_0 = -15.6$ MeV (binding energy). It is possible to change any of these numbers and we have used here more typical values for these quantities (except for $m_5 R$) presented by hadronic models [33,34]. For the quantities mentioned, we fit the nucleon mass in the vacuum, and the saturation properties of the SNM. From these three constraints we obtain $2\lambda/R = 767$ MeV (found by imposing that $M^*_N(\rho = 0) = M_N$), $\sigma_0 = 96$ MeV and $G^2_\omega = 9.9 \times 10^{-5}$ MeV^{-2} (found by imposing the saturation properties of nuclear matter). Notice that it is not needed to furnish g_ω or m_ω individually, since they always appear in the equations of state in the form of $G^2_\omega = g^2_\omega/m^2_\omega$, exactly as in the linear Walecka model.

Since the free parameters of the model are determined, it is possible to calculate nuclear matter quantities at the saturation density. For instance, we obtain $K_0 = 253.71$ MeV. This value is in agreement with the range of 250 MeV $\leqslant K_0 \leqslant$ 315 MeV found in Ref. [32].

The density dependence of the energy per nucleon and effective mass are presented in Fig. 1, where we show a comparison between the predictions of the MHD model and some parametrizations related to: (i) the linear Walecka model named as LHS [31]; (ii) more sophisticated QHD models, namely, BKA20 [35], BSR10 [36], and IU-FSU [37]; and (iii) a particular parametrization of the MQMC model [5] in which ρ_0, B_0 and K_0 are the same as in the MHD model. In particular, the parametrizations listed in (ii) belong to a set of "consistent" models that simultaneously satisfy constraints related to symmetric nuclear matter, pure neutron matter, and those coming from a range of possible values of the symmetry energy and other bulk parameters, all of them evaluated at the saturation density [33,38]. One can verify that the energy density of the MHD model is more comparable with the consistent QHD parametrizations instead the linear Walecka model. However, the effective nucleon mass curve of the MHD model is closer to that predicted by the MQMC one.

In Fig. 2 we analyze the MHD model against the SNM constraints regarding the pressure density dependence. They are represented in the figure by the band regions. In the first one (left panel), the band is constructed from the experiment of kaon condensation in heavy ion collisions [12]. In the second, the authors of Ref. [13] established the constraint from the experimental data on the motion of ejected matter in the energetic nucleus-nucleus collisions. Measurements of the particle flow in the collisions of ^{197}Au nucleus, at incident kinetic energy per nucleon varying from about 0.15 to 10 GeV, were used in order to produce the band region displayed in Fig. 2 (right panel). One can notice that the MHD model is in complete agreement with both SNM constraints.

We also explored the large density domain up to $\sim 50\rho_0$ verifying that σ increases to about σ_0 and in practice the situation of $\sigma \gg \sigma_0$ is not reached. Our model, although describing well the NM saturation properties and the flow constraint up to $5\rho_0$ (Fig. 2), doesn't reach the phase transition. The phase transition is found, for example, when considering the AdS/Reissner-Nordström

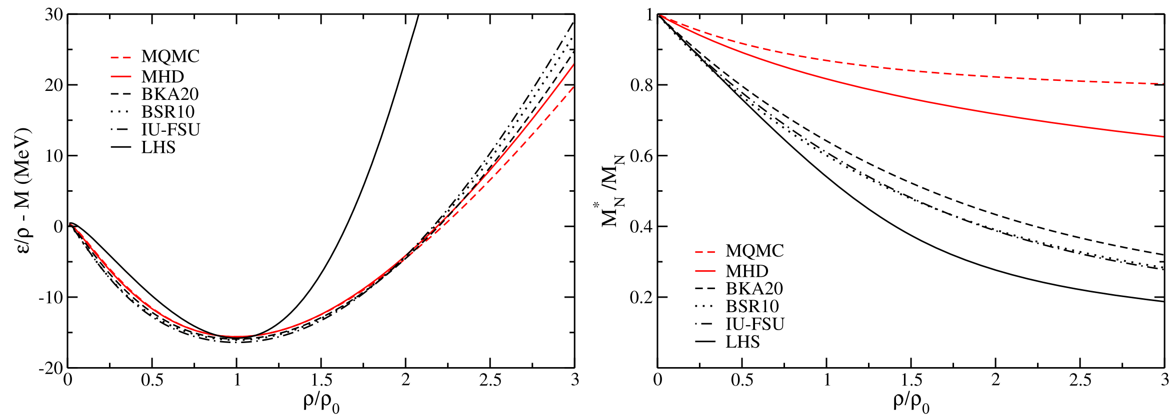

Fig. 1. Energy per nucleon (left panel) and M_N^*/M_N (right panel) as a function of ρ/ρ_0 (SNM) for the MHD model in comparison with some relativistic models, namely, BKA20 [35], BSR10 [36], and IU-FSU [37]. Also displayed a Walecka model, namely, LHS [31] and the MQMC one [5].

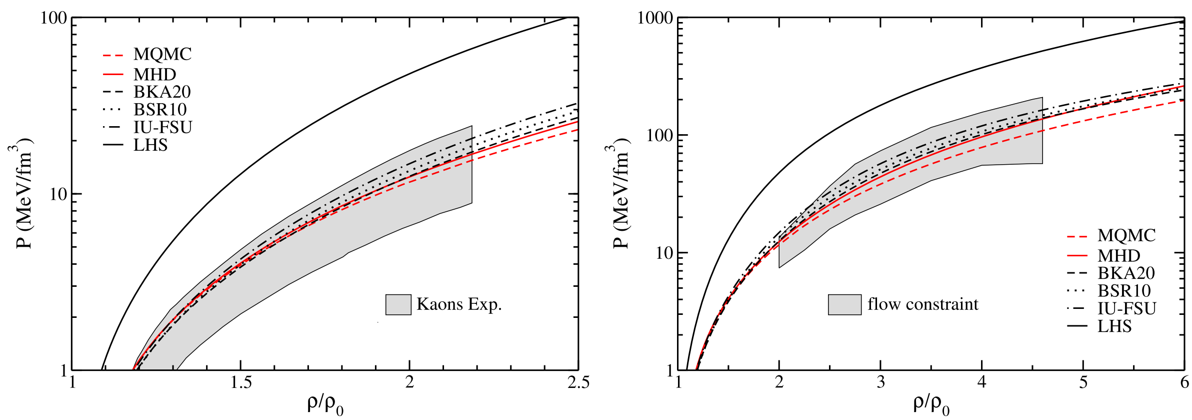

Fig. 2. $P \times \rho/\rho_0$ for SNM described by the MHD model in comparison with LHS, BKA20, BSR10, and IU-FSU parametrizations, along with the MQMC model. Bands: data extracted from Refs. [12] (left panel) and [13] (right panel).

metric to describe the nuclear medium effect on the hadron (see e.g. [23]). This indicates that further improvements have to be implemented in the model to address the phase transition issue appearing at much larger densities.

As a last analysis, we investigate the nucleon response to the external scalar field. It is now quantitatively illustrated in Fig. 3 for several different densities. We remind that both the strength of the UV conformal potential and the harmonic confinement are damped as a function density as the scalar background field given by Eq. (22) grows. The two expected effects in the nucleon state exhibited by the reduced string amplitude from the solution of the eigenvalue equation (9) with the medium modified potential (12) are seen in the figure. The reduced amplitude swells and the nucleon grows in size due to the decrease in the strength of the harmonic potential with density. An unexpected effect already pointed out in our previous discussion of the medium modified potential is that the asymptotic wave function in the UV region is depleted and the power law behavior for z going to zero is damped and associated with a smaller exponent, which implies that at large transverse momentum the wave function will decrease slower than the vacuum one, and correspondingly the valence parton distribution at the end points would presumably have a softer behavior at finite densities, and eventually with observable consequences.

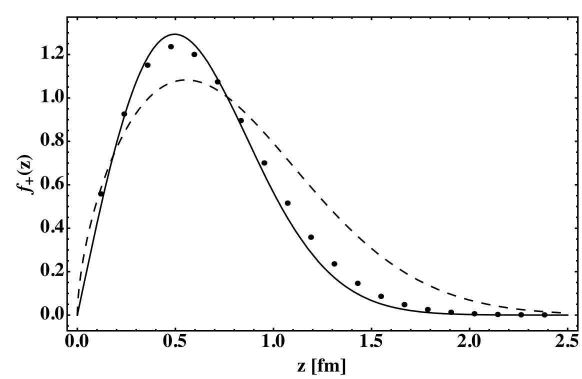

Fig. 3. Reduced string amplitude as a function of the holographic variable for the vacuum and at finite density. Results for $f_+(z)$ in the vacuum are given by the solid line, for $\rho = 0.35\rho_0$ ($\sigma = 0.1\sigma_0$) are given by the full circles, and for $\rho = 1.93\rho_0$ ($\sigma = 0.4\sigma_0$) are given by the dashed line.

7. Summary and conclusions

The Medium-modified Holographic-hadron Dynamics applied to symmetric nuclear matter satisfies all the known experimental constraints with just a few free adjustable parameters. We should stress that our computation in MHD is different from the usual MQMC computation as we do not involve any explicit quark degrees of freedom and their coupling with the ambient scalar and vector mean fields. Our holographic paradigm avoids any such not-well-known details but is capable of describing the medium-modification of the nucleon effective mass and internal structure, in consistence with nuclear matter saturation properties and the constraints coming from the density dependence of the thermodynamical pressure. The holographic nucleon swells and in addition the UV behavior is damped. This last property can also lead to observable effects reflecting an average leakage of partons to the nuclear medium when density is increased. Both characteristics signalize the route towards the deconfinement of the internal nucleon degrees of freedom. We intend to study other constraints to be verified for asymmetric matter, which demands a generalization of the model and would be useful for the physics of compact stars.

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Appendix A. Definitions of curved space-time quantities

We give below the standard expressions of the spinor algebra elements in curved space-time, which completes the definition of the quantities entering in the medium modified nucleon action. We start by defining the Dirac matrices in curved space-time:

$$\Gamma^M = e^M_a \gamma^a \,, \tag{A.1}$$

where the "vierbein" e^a_M defines a local Lorentzian frame such that the space-time interval can be written as

$$ds^2 = \eta_{ab}\,\theta^a\,\theta^b \,, \tag{A.2}$$

with $\eta_{ab} = \mathrm{diag}(1, -1, -1, -1, -1)$ being the Minkowski metric and $\theta^a = e^a_M\,dx^M$. The covariant derivative is

$$D_M = \partial_M + \frac{1}{4}\omega^{ab}_M \sigma_{ab} \tag{A.3}$$

with

$$\sigma_{ab} = \frac{1}{2}\Big(\gamma_a\gamma_b - \gamma_b\gamma_a\Big) \,, \tag{A.4}$$

and the spin connection [39]

$$\omega^{ab}_M = \frac{1}{2}\,e^{Na}\left(\partial_M e^b_N - \partial_N e^b_M\right) - \frac{1}{2}e^{Nb}\Big(\partial_M e^a_N - \partial_N e^a_M\Big) - \frac{1}{2}e^{Aa}e^{Bb}\Big(\partial_A e_{Bc} - \partial_B e_{Ac}\Big)e^c_M. \tag{A.5}$$

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