Nucleon flow and dilepton production in heavy-ion collisions

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Abstract

Nucleon flow in Au+Au collisions at 1 GeV/nucleon region and dilepton spectra in S+Au collisions at SPS energies are analysed in the relativistic transport model. They are shown to be sensitive to the nucleon vector and scalar potentials, respectively, and are thus useful probes of these potentials in dense matter. A recently developed effective Lagrangian with self-interactions of vector as well as scalar fields is found to describe both data reasonably well.
One of the primary motivations of high-energy heavy-ion collisions is to study the properties of hadrons in dense matter, which are expected to reflect the chiral symmetry breaking in vacuum and its restoration at high temperature and/or density, the so-called chiral phase transition [1]. Closely related to this is the study of deconfinement, namely, the formation of quark-gluon plasma in heavy-ion collisions [2]. The properties of dense matter that can be extracted from heavy-ion collisions are also very useful for astrophysics problems, such as the properties of neutron stars [3]. There are basically two types of observables that can be considered as ‘clean’ probes of hadronic properties in dense matter. One of these are the various collective ‘flows’ of hadrons that are sensitive to the entire dynamical process of heavy-ion collisions, and the other is the electromagnetic observables such as photon and dilepton spectra that are not affected by strong final-state interactions and thus carry information about the early stage of heavy-ion collisions.

Collective flows of nucleons and light fragments in heavy-ion collisions have been used to study the momentum as well as density (related to equation of state of equilibrium nuclear matter) dependence of the nucleon potential [4–7]. In Boltzmann-Uehling-Uhlenbeck (BUU) calculations, it has been found that a soft equation of state with a momentum dependent nucleon potential describes well the experimental data [7]. In relativistic transport models [8,9] based on various Walecka-type $\sigma$-$\omega$ models [10], the corresponding Schrödinger equivalent potential is explicitly momentum dependent. In the mean-field approximation, it increases linearly with nucleon kinetic energy [11]. In order to describe experimental data on flow in the 1 GeV/nucleon region in the mean field approximation, it was found that one has to use a relatively weak vector potential with $g_\omega^2/4\pi \approx 4.0$, and consequently also a weak scalar potential [12]. The magnitudes of these potentials are much smaller than those in the Walecka linear $\sigma$-$\omega$ model (hereafter referred to as Walecka model) [10].

Photon and dilepton spectra have also been studied extensively, both experimentally and theoretically, especially for heavy-ion collisions at SPS energies. A particular interesting observation from these experiments is the enhancement of low-mass dileptons in heavy-ion collisions as compared to proton-induced reactions [13,14]. Theoretical calculations from
various groups with different dynamical models converge to one conclusion, namely, medium effects are needed to explain the data \[^{13,16}\]. Based on the initial conditions provided by the relativistic quantum molecular dynamics (RQMD) \[^{17}\], we found that the data can be well accounted if the rho meson mass decreases at the same rate as the nucleon effective mass, i.e. \[^{18}\],

\[
\frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{m_N^*}{m_N},
\]

\(1\)

with the nucleon effective mass obtained from the Walecka model \[^{15}\].

There are, however, concerns about the use of Walecka model. This model does not describe nuclear matter saturation properties well; especially a compression modulus of about 560 MeV is simply too large as compared with the empirical value of about 200 MeV. The use of the Walecka model for heavy-ion collisions in the 1 GeV/nucleon region would overpredict the nucleon flow data, even after the incorrect momentum dependence in the mean-field potential is properly taken care of, as we shall discuss later.

The main purpose of this Letter is to show that there are effective chiral Lagrangians that can describe consistently both the flow and dilepton data, as well as nuclear matter and finite nuclei properties. We will further show that the nucleon flow is chiefly sensitive to the vector potential, while the shape of dilepton spectra is mainly determined by the scalar potential. They can thus be individually used to probe these potentials at higher densities. This separation is important for studies of hyperon and kaon properties in dense matter.

The effective Lagragian we use in this study is the one recently developed by Furnstahl, Tang, and Serot based on chiral symmetry considerations and the naturalness argument \[^{19,20}\]. They introduced, in addition to the self-interaction of the scalar field, the self-interaction of the vector field and coupling between the scalar and the vector field. In their energy density functional formalism, the energy density for the symmetric nuclear matter is given by \[^{20}\]

\[
\mathcal{E}(\Phi, W; \rho_B) = W \rho_B - \frac{1}{2C_V^2} W^2 + \alpha m_N \Phi W^2 - \frac{\zeta}{24} W^4
\]
\[
\frac{1}{2C_S^2} \Phi^2 + \frac{\kappa}{6} \Phi^3 + \frac{\lambda}{24} \Phi^4 + \frac{4}{(2\pi)^3} \int d^3p \sqrt{p^2 + m_N^*}^2,
\]

where \(m_N^* = m_N - \Phi\) and \(\Phi\) and \(W\) are the scalar and vector fields, which couple to nucleon with coupling constants \(C_S\) and \(C_V\), respectively. The scalar field shifts the nucleon mass, and the vector field its energy. If \(\zeta\) and \(\bar{\alpha}\) are zero, this reduces to the usual non-linear \(\sigma\)-\(\omega\) model [21]. If furthermore \(\bar{\kappa}\) and \(\bar{\lambda}\) are set to zero, we recover the original linear Walecka model [10]. The introduction of the vector field self-interaction and the coupling between the vector and scalar fields are useful for making a relatively soft equation of state, and at the same time producing a small nucleon effective mass.

By fitting to nuclear matter as well as finite nuclei properties, Furnstahl et al. [19,20] proposed a number of parameter sets. Here we will use one of these as listed in the first row of Table 4 of Ref. [20], which we denote as the FTS-T1 model. This parameter set leads to a saturation density of about 0.15 fm\(^{-3}\), with a binding energy of about 16 MeV. The nucleon effective mass \(M_N^*/M_N\) and the compression modulus at nuclear matter density are about 0.6 and 200 MeV, respectively. We show in Fig. 1(a) the nucleon effective mass as a function of density. The dotted curve shows the nucleon effective mass in the Walecka model [10]. Up to 3\(\rho_0\) they are very similar to each other.
FIG. 1. (a) Effective mass of nucleon (solid and dotted curve) and constituent quark mass (dashed curve) as calculated in the NJL model with bare quark mass of 5 MeV, (b) vector potential, (c) density derivative of vector potential, and (d) Schrödinger equivalent potential in the FST-T1 model and the Walecka model.

Also of interest is the comparison of the vector potential with and without the vector field self-interaction and vector-scalar coupling. When $\zeta$ and $\bar{\alpha}$ are zero, the vector potential is simply given by $C_V \rho_B$, so it rises linearly with density as in the Walecka model. The vector potential in Walecka model ($g_\omega^2/4\pi \approx 10.6$) is shown in Fig. 1(b) by the dotted curve, and compared with that from the FST-T1 model ($g_\omega^2/4\pi \approx 12.0$). At low densities where self-interaction terms are unimportant, the vector potential in the FST-T1 model is larger than that in the Walecka model, because of a larger vector coupling constant in the
former. However, as density increases, the high-order terms become important, and reduce the vector potential in the FST-T1 model. Around $3\rho_0$ the vector potential reduces from about 810 MeV in the Walecka model to about 670 MeV in the FST-T1 model. We will show that this bending down of the vector potential is very important to reproduce correctly the nucleon flow data, as it also reduces the slope, $dW/d\rho$, that enters the Hamilton equation of motion in the transport model which changes nucleon momentum. This is shown in Fig. 1(c) and compared with that in the Walecka model which is just the coupling constant $C_V$. This effect also softens the nuclear equation of state and helps to reduce the maximum mass of neutron stars [22]. On the microscopic level, the Dirac-Brueckner-Hartree-Fock (DBHF) calculation also shows the nonlinear density dependence of the vector potential [23].

On the mean-field level, the scalar and vector potentials are dependent only on density but not on momentum. Higher-order contributions introduce momentum dependence. In the DBHF calculation of ter Haar and Malfliet [24], this momentum dependence was studied, and the scalar and vector potentials were found to decrease with momentum. Empirical information about this comes mainly from the Dirac phenomenology analysis of the intermediate-energy proton-nucleus scattering [25]. In the present study we use a schematic approach to take account of this momentum dependence. At each local density, we solve the FST-T1 model in the mean-field approximation and obtain nucleon scalar and vector potentials that are momentum independent. The effective potentials for a nucleon with kinetic energy $E_{\text{kin}}$ (relative to its local cell) are then obtained by scaling the momentum independent potentials with the momentum dependence extracted from the Dirac phenomenology [25]. The Schrödinger equivalent potential obtained in this way are shown in Fig. 1(d) and found to be in good agreement with Dirac phenomenology for both the FST-T1 and the Walecka model.

We note that this treatment of the momentum dependence is not fully self-consistent. Since the introduction of the momentum dependence changes the equilibrium nuclear matter properties, a self-consistent procedure is required to satisfy both the equilibrium and nonequilibrium properties. This amounts to a small change of the parameters in the original
model and also some small changes in the fitting of Dirac phenomenology. Since the energy scale involved in equilibrium nuclear matter problem is much smaller than that in the initial stage of high-energy heavy-ion collisions, the effect of this self-consistent procedure on our flow results is expected to be unimportant.

Our results for nucleon flow parameter $F$ in Au+Au collisions in the 1 GeV/nucleon region are shown in Fig. 2 together with the experimental data from the EOS Collaboration [5]. The cascade calculation which does not include any mean field potential accounts already for about 2/3 of the observed flow. This is consistent with the results of BUU model of Ref. [7]. In ARC calculations [26], however, nucleon flow turns to be somewhat stronger and is thus close to the data, since an effectively repulsive trajectory is used for two-body scattering.

![FIG. 2. nucleon flow parameter in Au+Au collisions based on various effective Lagrangians.](image)

The result of Ref. [12] using the non-linear $\sigma$-$\omega$ model is shown in Fig. 2 by the open square. The flow parameter is about 280 MeV and is in good agreement with the data.
Although no energy correction was introduced in Ref. [12], because of the use of relatively weak scalar and vector potentials, the Schrödinger equivalent potential in the non-linear $\sigma$-$\omega$ model turns out to be in reasonable agreement with the Dirac phenomenology.

As mentioned, the Walecka model produces too much flow. The nucleon flow parameter obtained with the Walecka model without the momentum dependence correction (M.D.C.) is shown in Fig. 2 by the open triangle, while that with the M.D.C. is shown by solid triangle. The flow parameter in the first case is about 520 MeV, and is much too large as compared with the data. After including the M.D.C., which reduces the repulsion in the initial stage, the flow parameter reduces to about 450 MeV, which is still too large as compared to the data.

The result of the FST-T1 model without the M.D.C. is shown in the figure by the solid square, and is about 380 MeV. This is considerably smaller than that of the Walecka model with and without the M.D.C., but somewhat larger than the data. The results of the FST-T1 model with the M.D.C. are shown in Fig. 2 by open circles connected by solid lines. At 1 GeV/nucleon, the flow parameter reduces to about 330 MeV and is in now good agreement with the data, as is the case at other beam energies. We can thus conclude that with a proper correction for the momentum dependence, the FST-T1 model can explain the nucleon flow in heavy-ion collisions at 1 GeV/nucleon region quite well.

At $\rho_0$ and below, the scalar and the vector potentials, as well as the corresponding Schrödinger potentials in the FST-T1 model and Walecka model are very much the same (see Fig. 1). Actually, the scalar potentials in the two models agree with each other up to $3\rho_0$. Then why do they generate substantially different nucleon flow? The reason lies in the difference in their vector potentials at high densities. Because of high-order terms involving vector field self-interaction and vector-scalar coupling, the vector potential in the FST-T1 model becomes smaller than that in the Walecka model at high densities, thus providing less repulsion. Also the slope of the vector potential, $dW/d\rho$, gets smaller at high densities, providing less repulsive force. The nucleon flow is indeed sensitive to nucleon vector potential at high densities ($2-3\rho_0$ in Au+Au collisions).
In Fig. 3 the dilepton spectra in central S+Au collisions at 200 GeV/nucleon obtained in the FST-T1 model is shown. The calculations were performed as in Ref. [15] but with the Walecka model replaced by the FST-T1 model. The vector meson masses were assumed to scale like the nucleon mass, as in Eq. (1). It is seen that the fit with the in-medium meson masses is acceptable, although somewhat lower than the center of the experimental points in the low-mass region. Given the similarity between scalar fields in the FST-T1 and the Walecka model, the similarity in the dilepton production is not surprising.

![FIG. 3. Dilepton spectra in central S+Au collisions at 200 GeV/nucleon with free (dotted curve) and in-medium (solid curve) meson masses. The experimental data from Ref. [13] are shown by solid circles, with systematic errors given by bars. Brackets represent the square root of the quadratic sum of the systematic and statistical errors.](image)

Note that the nucleon flow (coming from the Vlasov part of the transport model) depends chiefly on the vector interaction. The force acting on a nucleon is proportional to the spatial derivative of its energy, $(p^2 + m_N^2)^{1/2} + W$. In the region of densities important for flow $(2-3\rho_0)$, the nucleons behave essentially as massless particles of momentum $p$ in a vector
potential $W$, since $m_N^*$ is small compared to $p$. On the other hands, the shape of the dilepton spectra depends almost completely on the scalar field, since the effective mass of vector mesons ($\rho, \omega$), and hence the dilepton mass, are related to the nucleon scalar field through Eq. (1). From the fitting to the CERES data, it is found that the scalar field must be sufficiently strong to reduce significantly the nucleon effective mass; and through Eq. (1), the effective mass of vector mesons.

We should remark that the vector mean field depends on the ratio of $g_{\omega NN}^*/m_\omega^*$. If $m_\omega^*$ decreases in medium like $m_\rho^*$, then $g_{\omega NN}^*$ must also decrease so that the vector potential increases at most linearly with density. The vector coupling is expected to scale in theories which treat the vector mesons as gauge particles of the hidden symmetry [27]. Unfortunately, it is difficult to calculate quantitatively in the nonperturbative regime discussed here. However, the nucleon flow does empirically determine the ratio $g_{\omega NN}^*/m_\omega^*$ to be independent of density at low densities and to decrease slightly at high densities.

Recently, Brown, Buballa, and Rho [28] argue for a chiral restoration transition that is mean field in the NJL model. In this case the scalar coupling $g_{\sigma NN}$ should remain unchanged through the transition. Brown et al find that the transition takes place at $\rho_c \leq 3\rho_0$. The NJL model has dropping scalar meson mass, because $m_\sigma^* = 2m_Q^*$, where $m_Q^*$ scales with density. Once one introduces a bare quark mass of about 5 MeV, however, $m_Q^*$ does not drop so rapidly, as shown in Fig. 1(a). At $3\rho_0$, $m_Q^* \approx 70$ MeV, which is just about $1/3$ of the $m_N^*$ at that density in the FST-T1 model. The vector field in NJL does not participate in the phase transition, and must be put in “by hand”. Thus we can say that the constituent quark mass in the NJL model, once bare quark mass are included, is about the same in the the density region $\rho \approx 3\rho_0$, as in the FST-T1 model. Since dilepton calculation depends chiefly on the scalar field, it seems clear that the NJL model will produce about the same dileptons as the FST-T1 model. This is an important statement, because the NJL model has the symmetries of QCD. The Walecka-type models can be derived [29,30] so that they possess chiral symmetry in low order, but do not have relevant higher order chiral terms contained in the NJL model.
In summary, we used the effective Lagrangian recently developed by Furnstahl, Tang and Serot in the transport model analysis of nucleon flow and dilepton production in heavy-ion collisions. We found that the model describe both sets of data reasonably well. The ability to describe the dilepton spectra can be attributed to the strong scalar field of the model that reduce significantly the vector meson mass through Eq. (1). The ability to describe the nucleon flow data can be traced back to the inclusion of vector field self interactions that reduce the vector potential at higher densities.

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