Isospin Effects on Subthreshold Kaon Production at Intermediate Energies

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We show that in collisions with neutron-rich heavy ions at energies around the production threshold K^0 and K^+ yields probe the isospin-dependent part of the nuclear equation of state at high baryon densities. In particular, we suggest the K^0/K^+ ratio as a promising observable. Results obtained in a covariant relativistic transport approach are presented for Au + Au collisions at 0.8–1.8*A* GeV. The focus is put on the equation of state influence which goes beyond the collision-cascade picture. The isovector part of the in-medium interaction affects the kaon multiplicities via two mechanisms: (i) a symmetry potential effect, i.e., a larger neutron repulsion in n-rich systems, and (ii) a threshold effect, due to the change in the self-energies of the particles involved in inelastic processes. Genuine relativistic contributions are revealed that could allow one to directly "measure" the Lorentz structure of the effective isovector interaction.

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For at least two decades, particle production has been suggested as a useful tool to constrain the poorly known high density behavior of the nuclear equation of state (EOS) [1,2]. In particular, pion and (subthreshold) kaon productions have been extensively investigated both theoretically [2–8] and experimentally [9–11] in heavy ion collisions (HICs) in the energy range 1–2*A* GeV, leading to the conclusion of a soft behavior of the EOS at high densities; see the recent Refs. [12,13]. Kaons (K^0, K^+) appear as particularly sensitive probes since they are produced in the high density phase almost without subsequent reabsorption effects. At variance, antikaons ($\bar{K}^0$, $\bar{K}^-$) are strongly coupled to the hadronic medium through strangeness exchange reactions [12,14,15].

For the isovector part of the EOS, the suggested quantities to look at have been charge ratios and collective isospin flows for highly energetic nucleons and pions [16–21] and isospin transparency as expressed in transport ratios [22–24]. Controversial deductions arise from different relativistic and nonrelativistic models; see [25,26]. In this Letter, we propose the K^0/K^+ yield ratio as a good observable to constrain the high density behavior of the symmetry term.

We show that, within a covariant description of nuclear dynamics, from the K^0/K^+ ratios we can directly investigate the Lorentz structure, i.e., the scalar-vector decomposition of the isovector sector of the effective in-medium hadron Lagrangian. Some promising indications have been recently obtained in nuclear matter calculations [27]; here we present results for realistic open systems, i.e., for collisions of neutron-rich heavy ions in the energy range around the kaon production threshold (1.56*A* GeV).

Using a transport model, derived within the relativistic mean-field approximation (RMF) of quantum hadrodynamics [28], we analyze pion and kaon production in central ^{197}Au + ^{197}Au collisions in the 0.8–1.8*A* GeV beam energy range, with different RMF effective field choices for $E_{\rm sym}$. We will compare results of three Lagrangians with constant nucleon-meson couplings, nonlinear form (NL; see [18,26]), and one with density-dependent couplings (DDF; see [18]), recently suggested for apparent better nucleonic properties of neutron stars [29]. In order to isolate the sensitivity to the isovector components, we use models showing the same "soft" EOS for symmetric matter [18,26].

For the isovector part, in the simple NL choice the mean field is not isospin-dependent and the symmetry energy is just due to kinetic (Fermi) contributions. The NLρ model contains an isovector-vector effective field (ρ meson), which leads to a splitting of the vector self-energies between protons and neutrons and to a more repulsive force experienced by neutrons with respect to protons in neutron-rich matter [26]. In the NLρ model, an isovector-scalar δ field is also included, which gives an effective mass splitting between protons and neutrons [30,31].

With both ρ- and δ-meson couplings $f_{\rho,\delta}$, a transparent form of the symmetry energy can be derived [31]

$$E_{\rm sym} = \frac{1}{6}\frac{k_F^2}{E_F} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{m^*}{E_F}\right)^2\right]\rho_B, \qquad (1)$$

leading to a partial cancellation of scalar and vector components, equivalent to that of the σ and ω fields in the isoscalar sector. Since the δ field couples to the scalar density, f_δ is multiplied to a density-dependent quenching factor in Eq. (1). It is then clear that a suitable increase of the ρ coupling f_ρ in the NL$\rho\delta$ model is necessary to compensate the attraction due to the scalar δ field, in order to get the same bulk asymmetry parameter $a_4 = 30.5$ MeV at saturation [18,31]. Consequently, the inclusion of a δ field leads to a stiffer symmetry energy at high baryon densities [31] and to larger vector self-energies for nucleons, as discussed in Refs. [17,27]. At variance, in the DDF model the f_ρ is exponentially decreasing with density, resulting in a rather soft symmetry term at high density [18,29].

In the energy range considered here, the nucleon-nucleon inelastic channels can be restricted to the excitation of the lowest mass resonance $\Delta(1232)$ and perturbative kaon ($K^{+,0}$) production through baryon-baryon collisions $BB \to BYK$, where B stands for nucleons or resonances and Y for hyperons (Λ, $\Sigma^{\pm,0}$). Pions are produced via the decay of the $\Delta(1232)$ resonance and—after propagation and rescattering—can contribute to the kaon yield through collisions with baryons: $\pi B \to YK$. All of these processes are treated within a relativistic hadronic transport model of Boltzmann-Uehling-Uhlenbeck type, i.e., including a hadron mean-field propagation [32,33]. The latter point, which goes beyond the "collision-cascade" picture, is essential for particle production yields since it directly affects the energy balance of the inelastic channels. Further details can be found in Ref. [27], where all the parametrizations used for the corresponding cross sections are also specified.

Because of the $K^{+,0}$ long mean free path, their in-medium widths can be expected to be small and an on-shell quasiparticle treatment appears suitable. Here, as in Ref. [27], we do not generally use potentials for kaons and propagate them as free particles. The yield ratios suggested here will be less sensitive to potential effects [12].

When isovector fields are included, the symmetry potential energy in neutron-rich matter is repulsive for neutrons and attractive for protons. In a HIC, this leads to a fast, preequilibrium, emission of neutrons. Such a mean-field mechanism, often referred to as isospin fractionation [25,26], is responsible for a reduction of the neutron to proton ratio during the high density phase, with direct consequences on particle production in inelastic nucleon-nucleon collisions.

Threshold effects represent a more subtle question. The energy conservation in a hadron collision, in general, has to be formulated in terms of the canonical momenta, i.e., for a reaction $1 + 2 \to 3 + 4$ as

$$s_{\text{in}} = (k_1^\mu + k_2^\mu)^2 = (k_3^\mu + k_4^\mu)^2 = s_{\text{out}}. \quad (2)$$

Since hadrons are propagating with effective (kinetic) momenta and masses, an equivalent equation should be formulated starting from the effective in-medium quantities $k^{*\mu} = k^\mu - \Sigma^\mu$ and $m^* = m + \Sigma_s$, where Σ_s and Σ^μ are the scalar and vector self-energies, respectively, depending on the isovector channel structure. In particular, for the general $\sigma\omega\rho\delta$ case, one obtains for the self-energies of protons and neutrons:

$$\Sigma_s(p, n) = -f_\sigma \rho_s \pm f_\delta \rho_{s3}, \quad (3)$$

$$\Sigma^\mu(p, n) = f_\omega j^\mu \mp f_\rho j_3^\mu, \quad (4)$$

(upper signs for neutrons), where $\rho_s = \rho_{sp} + \rho_{sn}$, $j^\alpha = j_p^\alpha + j_n^\alpha$, $\rho_{s3} = \rho_{sp} - \rho_{sn}$, and $j_3^\alpha = j_p^\alpha - j_n^\alpha$ are the total and isospin scalar densities and currents and $f_{\sigma,\omega,\rho,\delta}$ are the coupling constants of the various mesonic fields [34].

In reactions where nucleon resonances, especially the different isospin states of the Δ resonance, and hyperons enter, also their self-energies are relevant for energy conservation. We specify them in the usual way according to the light quark content and with appropriate Clebsch-Gordon coefficients [27].

In the most general case, the isovector-scalar and vector self-energies enter the new threshold condition for a given inelastic process [27]

$$s_{\text{in}} \geq (m_3^* + \Sigma_3^0 + m_4^* + \Sigma_4^0)^2 - (\mathbf{\Sigma}_3 + \mathbf{\Sigma}_4)^2. \quad (5)$$

The condition of energy conservation in inelastic hadron collisions will influence the particle production in two different ways. On one hand, it will directly determine the thresholds and, thus, the multiplicities of a certain type of particles, in particular, of the subthreshold ones, as here for the kaons. On the other hand, it may favor or penalize reactions, because the self-energies in the final channel are more attractive or repulsive than in the initial one, and, consequently, the phase space in the final channel is larger or smaller.

We remark that, while the scalar and vector isovector fields tend to cancel in the symmetry term [see Eq. (1)], they can have very different dynamical effects, as already noted in the flow analysis of Ref. [17]. As an example, nn collisions excite $\Delta^{-,0}$ resonances which decay mainly to π^-. In a neutron-rich matter, the mean-field effect pushes out neutrons, making the matter more symmetric and, thus,

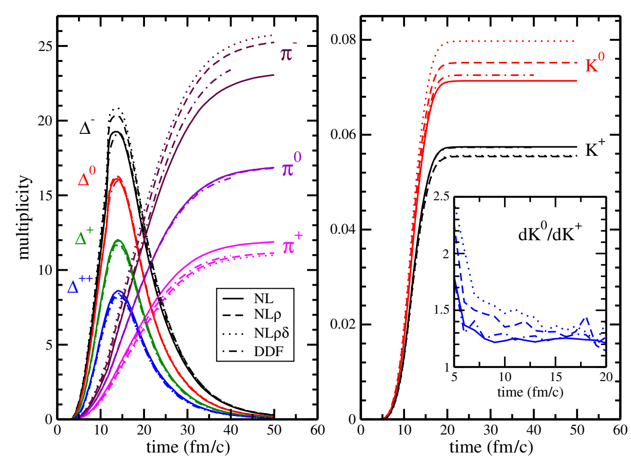

FIG. 1 (color online). Time evolution of $\Delta^{\pm,0,++}$ resonances, pions $\pi^{\pm,0}$ (left), and kaons $K^{0,+}$ (right) for a central ($b = 0$ fm impact parameter) Au + Au collision at 1A GeV incident energy. Transport calculation using the NL, NLρ, NL$\rho\delta$, and DDF models for the isovector part of the nuclear EOS are shown. The inset shows the differential K^0/K^+ ratio as a function of the kaon emission time.

decreasing the π^- yield. The threshold effect, on the other hand, is increasing the rate of π^-'s due to the enhanced production of the Δ^- resonances: Now the $nn \to p\Delta^-$ process is favored (with respect to $pp \to n\Delta^{++}$) since more effectively a neutron is converted into a proton.

Figure 1 reports the temporal evolution of $\Delta^{\pm,0,++}$ resonances and pions ($\pi^{\pm,0}$) (left panel) and kaons ($K^{+,0}$) (right panel) for central Au + Au collisions at $1A$ GeV. Results are shown for all of the tested models. It is clear that, while the pion yield freezes out at times of the order of 50 fm/c, i.e., at the final stage of the reaction (and at low densities), kaon production occurs within the very early stage of the reaction, and the yield saturates at around 20 fm/c. Kaons are then suitable to probe the high density phase of nuclear matter. This is not the case for pions, which suffer from reabsorption and isospin exchange processes that modify both the absolute primordial yield and the π^-/π^+ ratio.

In fact, from the left panel in Fig. 1, we see that the pion results for different models are rather similar, and, thus, pion multiplicities depend only weakly on the isospin part of the nuclear mean field. However, a slight increase (decrease) in the π^- (π^+) multiplicity is observed when going in the direction of larger f_ρ couplings NL $\to$ DDF $\to$ NLρ $\to$ NL$\rho\delta$. For pion production at $1A$ GeV, the "threshold" mechanism still appears to overcompensate the isospin distillation.

Such interplay between the two mechanisms cannot be fully included in a nonrelativistic dynamics, in particular, in calculations where the baryon symmetry potential is treated classically [16,19–21]. A typical example is the strength of the isovector-vector ρ coupling which is linked to the symmetry energy but is largely varying with the Lorentz structure of the isovector interaction.

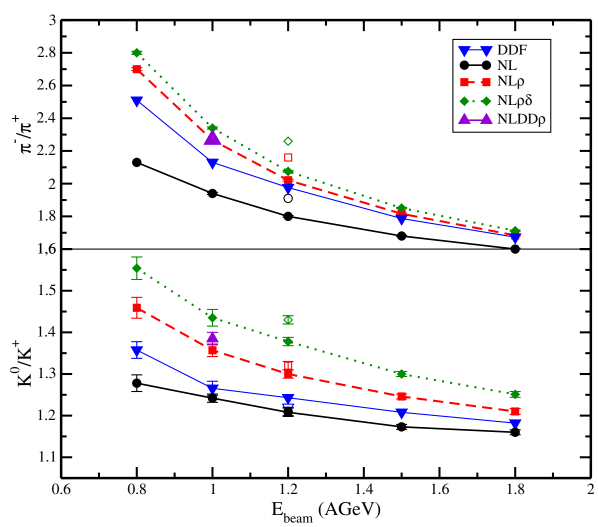

FIG. 2 (color online). π^-/π^+ (upper) and K^+/K^0 (lower) ratios as a function of the incident energy for the same reaction and models as in Fig. 1. In addition, we present, for $E_{\rm beam} = 1A$ GeV, NLρ results with a density-dependent ρ coupling (triangles); see text. The open symbols at $1.2A$ GeV show the corresponding results for a ^{132}Sn + ^{124}Sn collision, more neutron-rich. Note the different scale for the π^-/π^+ ratios.

As seen in the right panel inFig. 1, a similar argument holds for K^0 and K^+ mesons, which come mainly from nn (or $\pi^- n$) and pp (or $\pi^+ p$) collisions, respectively, and thus exhibit the same trend as π^- and π^+. However, the isospin effect in this case is more pronounced because the changes in the self-energies for the different models play a more crucial role close to the kaon production threshold. Moreover, as shown in the inset in Fig. 1, larger effects are expected for early emitted kaons, reflecting the initial N/Z of the system.

Finally, the beam energy dependence of the π^-/π^+ (left) and K^0/K^+ (right) ratios is shown in Fig. 2. At each energy, we see an increase of the yield ratios with the models NL $\to$ DDF $\to$ NLρ $\to$ NL$\rho\delta$. The effect is larger for the K^0/K^+ compared to the π^-/π^+ ratio. This is due to the subthreshold production and to the fact that the isospin effect enters twice in the two-step production of kaons; see [35]. Between the two extreme DDF and NL$\rho\delta$ isovector interaction models, the variations in the ratios are of the order of 14%–16% for kaons, while they reduce to about 8%–10% for pions. Interestingly, the iso-EOS effect for pions is increasing at lower energies, when approaching the production threshold.

We have to note that in a previous study of kaon production in excited nuclear matter the dependence of the K^0/K^+ yield ratio on the effective isovector interaction appears much larger, about 10 times more for a system with the Au asymmetry (see Fig. 8 in Ref. [27]). The point is that in the nonequilibrium case of a heavy ion collision the asymmetry of the source where kaons are produced is, in fact, reduced by the $n \to p$ "transformation," due to the favored $nn \to p\Delta^-$ processes. This effect is almost absent at equilibrium due to the inverse transitions; see Fig. 3 in Ref. [27]. Moreover, in infinite nuclear matter even the fast neutron emission is not present.

In order to further stress the distinction between effects of the stiffness of the symmetry energy and the detailed Lorentz structure of the isovector part of the effective Lagrangian, we also show the results for the K^0/K^+ with another parametrization of $E_{\rm sym}$. This model, NLDDρ, is a variant of NLρ with a density-dependent ρ coupling, built in such a way as to reproduce the same stiffer $E_{\rm sym}(\rho_B)$ of the NL$\rho\delta$ model (see also Ref. [17]). The results for the π^-/π^+ and K^0/K^+ ratios are shown in Fig. 2 for $E_{\rm beam} = 1.0A$ GeV as triangles. We see that they are closer to the NLρ results (with a constant f_ρ) than to the ones of the NL$\rho\delta$ choice which has the same isostiffness. This nicely confirms that the differences observed going from the NLρ to the NL$\rho\delta$ parametrization are not due to the slightly increased stiffness of $E_{\rm sym}(\rho_B)$ but more specifically to the competition between the attractive scalar δ field and the repulsive vector ρ field in the isovector channel, which leads to the increase of the vector coupling [see the comments to Eq. (1)].

In the same Fig. 2, we also report results at $1.2A$ GeV for the ^{132}Sn + ^{124}Sn reaction, induced by a radioactive beam, with an overall larger asymmetry (open symbols). The isospin effects are clearly enhanced.

From the present discussion, we conclude that subthreshold kaon production could provide a promising tool to extract information on the isovector part of the nuclear interaction at high baryon density. We have seen that, at beam energies below and around the kinematical threshold, the K^0/K^+ inclusive yield ratio is more sensitive to the Lorentz structure of $E_{\rm sym}$ than the π^-/π^+.

We stress the two most important results of our study: (i) We have shown that isospin effects are important not only at the mean-field level (isospin fractionation) but that they also influence significantly particle production cross sections. As a matter of fact, we observe that, for the reactions studied here, the modifications induced in the inelastic vertices represent the dominant effects. (ii) At relativistic energies, due to the Lorentz structure of the isovector nuclear interaction, the isotopic content of particle emission is not directly related to the symmetry energy value, but it can be rather considered as a measure of the strength of isovector-vector channel.

We note that the isospin effects on the kaon inclusive yield ratios at the freeze-out appear not too strong, although experimentally accessible. It seems important to select more exclusive kaon observables, in particular, with a trigger related to an early time K production. A transverse momentum selection of pion yields, corresponding to a higher density source, should also be rather sensitive to isospin effects, in particular, at lower energies, closer to the production threshold. A large asymmetry of the colliding matter is, in any case, of relevance. In this sense, our work strongly supports the study of particle production at the new relativistic radioactive beam facilities.

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[34] For the NL models in Eq. (3), the scalar density should be replaced by $\sigma(\rho_s)$, the solution of the nonlinear equation for the σ field [26,31].
[35] In the energy range explored here, the main contribution to the kaon yield comes from the pionic channels, in particular, from πN collisions and from the $N\Delta$ channel, which together account for nearly 80% of the total yield; see [27].