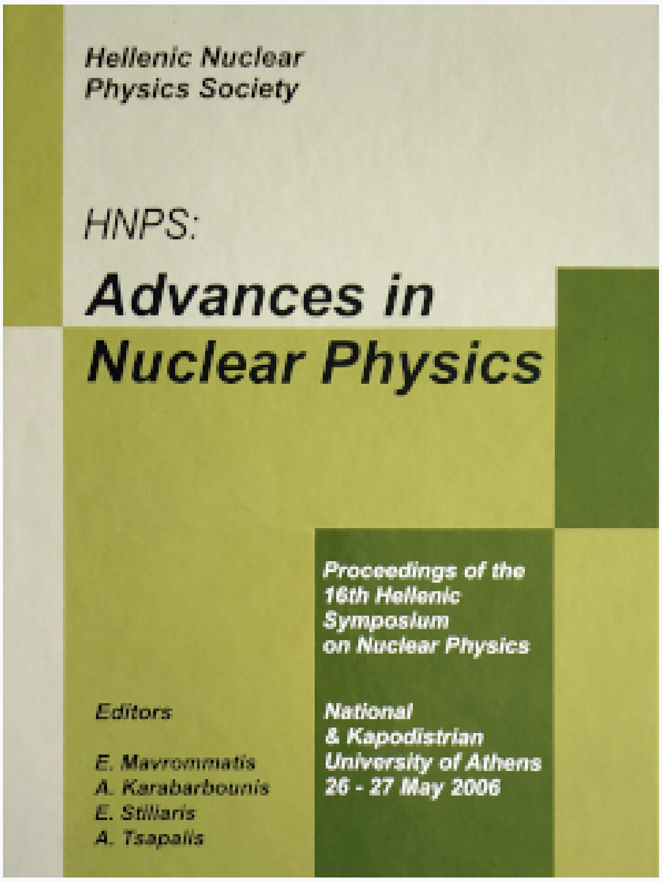
HNPS Advances in Nuclear Physics

Vol 15 (2006)

HNPS2006



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doi: 10.12681/hnps.2639

Particle Production in Heavy Ion Collisions at Intermediate Energies

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We investigate the influence of the in-medium modifications of nucleon-nucleon cross sections on the particle production in heavy ion collisions at intermediate energies. In particular, it is shown that the pion and kaon yields and their rapidity distributions are strongly affected by the density dependence of the *inelastic* cross sections. On the other hand, the particle ratios depend less on the in-medium behavior of the inelastic cross sections.

1. Introduction

The study of meson production in relativistic heavy ion collisions has provided important insight into the dynamics of heavy ion collisions and the formation and properties of compressed and heated hadronic matter [1,2]. The inclusive subthreshold production of strange hadrons in relativistic heavy ion collisions at intermediate energies (0.8-2 AGeV), has recently attracted considerable attention from both, the theoretical and experimental side. The main reason is that the study of strange particles, such as positive charged kaons, is relevant with the understanding of the strangeness enhancement in heavy ion collisions, which has been suggested as a possible signature of quark- gluon plasma formation in these reactions.

A suitable way to investigate the properties of hadronic matter at high baryon densities and temperatures, in heavy ion collisions at intermediate energies, is the relativistic transport model of Boltzmann- type [3]. In this model the reaction dynamics are influenced by the density and energy dependence of the nuclear mean field, particularly, by the nucleon -nucleon cross sections of elastic and inelastic binary collisions. The role of the nuclear mean field on the dynamics has been extensively studied in such dynamical situations. However, investigations for the role of different parameterization of the inelastic cross sections (with intermediate resonance production), on the dynamics of the collisions are rare. On the other hand, particle production, is used as a probe to determine the high density behavior of hadronic matter in heavy ion collisions. This is done by using phenomenological parameterization for the inelastic cross sections in free space. However, because of finite energy density, modifications of the cross section for binary collisions are expected. This is essentially due to the Pauli principle in intermediate colliding states, with respect to the ones in free space.

In the present work we have studied this important topic by applying density dependent inelastic cross sections in the collision integral. The transport analysis shows that particle yields and momentum distributions of pions significantly depend on the effective cross sections and can reproduce the experimental data reasonably well. In section 2 a brief description of the theory is given, while section 3 contains our calculations. The main results are summarised in section 4.

2. Theoretical description of collision dynamics

2.1. The RBUU equation

The theoretical description of HIC is based on the semiclassical kinetic theory of statistical mechanics, i.e. the Boltzmann Equation with the Uehling-Uhlenbeck modification of the collision integral [3]. The relativistic analogon of this equation is the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) equation [4]

$$\left[k^{*\mu}\partial_\mu^x + \left(k^*_\nu F^{\mu\nu} + M^*\partial_x^\mu M^*\right)\partial_\mu^{k^*}\right] f(x,k^*) = \frac{1}{2(2\pi)^9}$$
$$\times \int \frac{d^3k_2}{E^*_{\mathbf{k}_2}}\frac{d^3k_3}{E^*_{\mathbf{k}_3}}\frac{d^3k_4}{E^*_{\mathbf{k}_4}} W(kk_2|k_3k_4)\left[f_3 f_4 \tilde{f}\tilde{f}_2 - f f_2 \tilde{f}_3\tilde{f}_4\right] , \tag{1}$$

where $f(x,k^*)$ is the single particle distribution function. In the collision term the shorthand notations $f_i \equiv f(x,k_i^*)$ for the particle and $\tilde{f}_i \equiv (1 - f(x,k_i^*))$ for the hole distributions are used. The collision integral exhibits explicitly the final state Pauli-blocking while the in-medium scattering amplitude includes the Pauli-blocking of intermediate states.

The dynamics of the drift term, i.e. the lhs of eq.(1), is determined by the mean field. Here the attractive scalar field Σ_S enters via the effective mass $M^* = M - \Sigma_s$ and the repulsive vector field Σ_μ via the kinetic momenta $k^*_\mu = k_\mu - \Sigma_\mu$ and via the field tensor $F^{\mu\nu} = \partial^\mu\Sigma^\nu - \partial^\nu\Sigma^\mu$. The dynamical description according to (1) involves the strangeness propagation in the nuclear medium.

2.2. In-medium effects of NN cross sections

The in-medium cross sections for 2-body processes (see below) enter in the collision integral via the transition amplitude

$$W = (2\pi)^4\delta^4\left(k + k_2 - k_3 - k_4\right)(M^*)^4|T|^2 \tag{2}$$

with T the in-medium scattering matrix element. At intermediate relativistic energies up to the maximum threshold limit of kaon production, i.e. $E_{lab} = 1.58$ GeV, the main channels are (B, Y, K stand for a baryon (nucleons N or a Δ-resonance), hyperon and kaon, respectively)

- $BB \longrightarrow BB$ (elastic channels)
- $NN \longleftrightarrow N\Delta$ (Δ-production and absorption)
- $\Delta \longleftrightarrow \pi N$ (π-production and absorption)

- $BB \longrightarrow BYK$ (K-production from BB-channels)
- $B\pi \longrightarrow YK$ (K-production from $B\pi$-channels)

In the kinetic equation (1) both physical input quantities, the mean field (EoS) and the collision integral (cross sections) should be derived from the same underlying effective two-body interaction in the medium, i.e. the in-medium T-matrix; $\Sigma \sim \Re T\rho$, $\sigma \sim \Im T$, respectively $W \sim |T|^2$. However, in most practical applications phenomenological mean

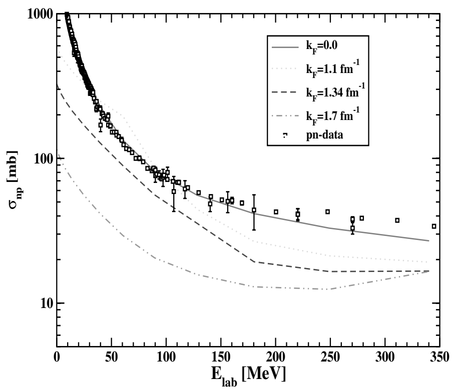

Figure 1. Elastic in-medium neutron-proton cross sections at various Fermi momenta k_F as a function of the laboratory energy E_{lab}. The free cross section ($k_F = 0$) is compared to the experimental total np cross section [12].

fields and cross sections have been used. In these models, the strategy is to adjust the parameters to the known bulk properties of nuclear matter around the saturation point, and to try to constrain the models at supra-normal densities with the help of heavy ion reactions [5,6]. Medium modifications of the NN cross section are usually not taken into account which works, in comparison to experimental data, astonishingly well [5–8]. However, in the kinematic regimes a sensitivity to the elastic NN cross section of the dynamical observables, such as collective flow and stopping [9,10] or transverse energy transfer, [11] has been observed.

Microscopic DBHF studies for nuclear matter above the Fermi energy regime showed a strong density dependence of the elastic [12] and inelastic [13,14] NN cross sections. In such studies one starts from the bare NN-interaction in the spirit of the One-Boson-Exchange (OBE) model by fitting the parameters to empirical nucleon-nucleus scattering and solves the structure equations of the nuclear matter many body problem in the T-matrix or ladder approximation. It is not the scope of the present work to go into further details. The inclusion of the Pauli-blocking effect in the *intermediate* scattering states of the T-matrix elements and their in-medium modifications, i.e. the density dependence of the nucleon mass and momenta, is important for such microscopic calculations. Of particular interest are thereby the in-medium modifications of the inelastic NN cross sections since they directly influence the production mechanism of resonances and thus the creation of pions. DBHF studies on inelastic NN cross sections are rare and limited in momentum [13]. For this reason we will discuss in the following the in-medium dependence of the elastic NN cross sections, which serves as a starting basis for the detailed discussion of the density dependence of the inelastic NN cross sections.

The microscopic in-medium dependence of the elastic cross sections can be seen in Fig. 1, where the energy dependence of the in-medium neutron-proton (np) cross section at Fermi momenta $k_F = 0.0, 1.1, 1.34, 1.7 fm^{-1}$, corresponding to $\rho \sim 0, 0.5, 1, 2\rho_0$ ($\rho_0 = 0.16 fm^{-3}$ is the nuclear matter saturation density) is shown. These results are obtained from relativistic Dirac-Brueckner (DB) calculations [12].

We have used here the same DBHF approach for the density bahavior of the *inelastic* cross sections, i.e. for processes of the type $NN \longrightarrow N\Delta$ with resonance production. Haar and Malfliet [13] have investigated this topic for infinite nuclear matter which results to a strong in-medium modification of the inelastic cross sections. However, these studies were limited in density and particularly in momentum. We have thus parameterized the

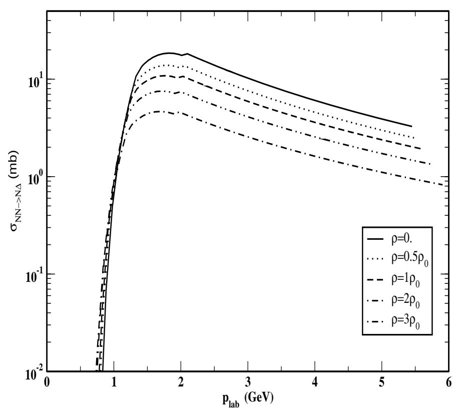

Figure 2. Momentum dependence of the effective DBHF cross section at various baryon densities ρ (in units of the saturation density $\rho_0 = 0.1854\ fm^{-3}$).

DBHF calculations with a function of the type $\sigma_{eff} = \sigma_{free}(E_{\rm lab})f(\rho)$ with σ_{free} taken from the standard free parametrizations of Ref.[13].

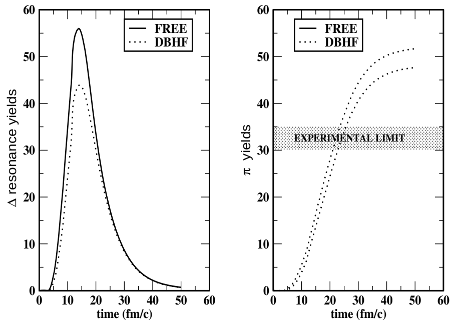

Figure 3. Time evolution of the Δ-resonances (left panel)and total pion yield (right panel) for a central ($b = 0\ fm$) Au+Au reaction at 1 AGeV incident energy. Calculations with free (solid lines) and effective (DBHF, dashed lines) are shown. The gray band on the right panel represents the experimental limits [15].

Fig.2 shows the energy dependence of the inelastic NN cross section at various densities as obtained from DBHF calculations [13] for symmetric nuclear matter. As in the case of elastic processes (see Fig.1), the inelastic one drops with increasing baryon density ρ, mainly due to the Pauli blocking of intermediate scattering states and the medium modification of the effective Dirac mass [13].

3. Results

In this section the results of the transport simulations are presented. The RBUU calculations with the effective (free) inelastic cross sections will be denoted as DBHF (FREE) in the following. In all the transport studies we have used the in-medium elastic cross sections of the same underlying DBHF approach [13]. For the nuclear mean field the $NL2$ parametrization of the non-linear Walecka model [4] is adopted, with a compression modulus of 200 MeV and a Dirac effective mass of $m^* = 0.82\ M$ (M is the bare nucleon mass). The momentum dependence enters via the relativistic treatment of the scalar and vector components of the baryon self energy. We start the discussion with the time evolution of the multiplicities of Δ resonances and pions, as is shown in Fig. 3. The maximum of the multiplicity of produced Δ-resonances occurs around 15 fm/c which corresponds to the time of maximum compression. Due to their finite lifetimes these resonances decay into pions (and nucleons) as $\Delta \longrightarrow \pi N$ (some of these pions are re-absorbed in the inverse process, i.e. $\pi N \longrightarrow \Delta$). This mechanism continues until all resonances decay, leading to a saturation of the pion yield for times $t \geq 50$ fm/c (the so-called freeze-out time), which corresponds to the experimentally measured one. The experimental pion multiplicity is schematically shown in Fig. 3 as the gray band for central Au+Au collisions [15]. We observe a moderate reduction of the resonances and therefore of the pion multiplicity using the DBHF inelastic NN cross sections, in consistency with the fall of the inelastic cross sections with increasing density (see again Fig. 2). The comparison with the experimental limits for the pion yield supports the inclusion of the medium dependence on the inelastic cross sections, but the theoretical calculations do not fit well the data. One reason is the difficulty in the experimental centrality selection of the reaction, whereas in the theoretical results a fixed impact parameter ($b = 0\ fm$) has been used. One should also note that the DBHF model is a parameter free approach [13]. The moderate in-medium effects on the yield of the resonances and the produced

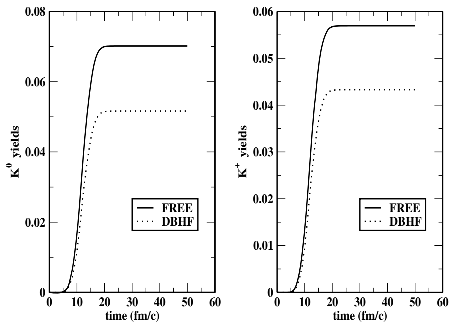

Figure 4. Time evolution of the K^0 (left panel) and K^+ (right panel) for the same reaction and models as in Fig. 3.

pions strongly affect the corresponding kaon multiplicities, as can be seen in Fig. 4. This is due to the fact that the leading channels for kaon production are $N\Delta \longrightarrow BYK$ and also the pionic ones. Thus, the kaon production is essentially a twostep process and the medium-modified σ_{inel} enters twice, leading to an increased sensitivity. The whole picture is summarized in Fig. 5 in terms of the stopping power, i.e. the rapidity distribution for pions and kaons. Again, the in-medium effect is only very moderate for the pions, but more pronounced for the kaons.

A crucial question is whether particle yield *ratios* are influenced by in-medium effects of the inelastic cross section. This question is of major importance, particularly for kaons and less for pions, since particle ratios have been widely used in determining the nuclear EoS at supra-normal densities in comparison to experiment. Fig. 6 shows the (π^-/π^+)- and (K^+/K^0)-ratios for central ($b = 0$ fm) Au+Au collisions at 1.0 AGeV incident energy using both the free and in-medium inelastic cross sections. We observe here that both the pionic and the kaonic ratio are not particularly affected by the inclusion of the in-medium effects in the inelastic cross sections. The pionic ratio depends moderately (about 20%) on the in-medium effects of the inelastic cross section, but the (K^+/K^0)-ratio is not particularly affected. A possible reason for the different behavior of the pionic and kaonic ratios may lie in the different time scales of the emission of the particles. In particular, kaons are created very early during the formation of the high density phase and are emitted from the compression region without undergoing any interaction with

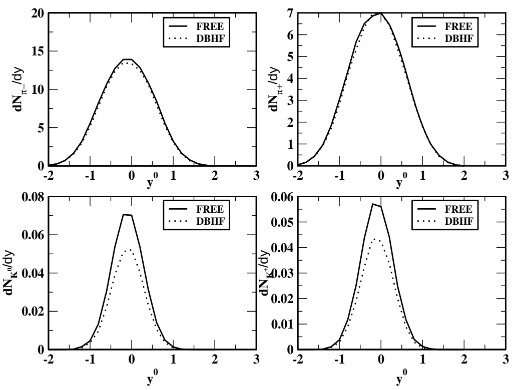

Figure 5. Rapidity distributions of π^- (top-left), π^+ (top-right), K^0 (bottom-left) and K^+ (bottom-right) for the same reaction and models as in Fig. 3.

the hadronic environment. Therefore one expects a direct connection between the high density behavior of the inelastic cross sections and the (K^+/K^0)-ratio. Pions, on the other hand, interact strongly with the medium via secondary re-absorption processes and thus are emitted from different stages of a collision. This influences the final (π^-/π^+)-ratio [16,17]. In conclusion, we find that the strangeness ratios are not sensitively influenced by in-medium modifications of the inelastic cross sections and thus they present a robust observable to investigate the isovector sector of the nuclear matter EoS.

4. Conclusions

We have investigated the role of the in-medium modifications of the inelastic cross sections on particle production in heavy ion collisions at intermediate energies, within a covariant transport equation of Boltzmann type. The same DBHF approach has been used for both, the elastic and inelastic NN cross sections. This approach provides in a parameter free manner the in-medium modifications of the imaginary part of the self energy in nuclear matter. Particle multiplicities and rapidity distributions have shown a strong sensitivity on this modifications. The pionic ratios, due to their strong secondary interaction processes with the hadronic environment, are moderately influenced by the density dependence of the inelastic cross sections. On the other hand, the (K^+/K^0)-ratio is not affected. This is mainly due to the long mean free path of the $K^{0,+}$.

More systematic studies are necessary to understand better the mechanism which leads to a relation between the in-medium modification of the inelastic cross sections and the particle ratios.

Acknowledgment This work is supported by BMBF, grand 06LM189 and the State Scholarships Foundation (I.K.Y.). Also is co-funded by European Union Social fund and

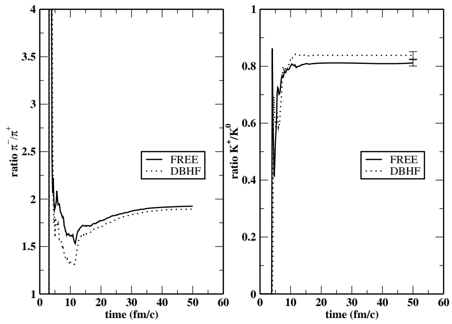

Figure 6. Time evolution of the π^-/π^+ (left panel) K^+/K^0 (right panel) ratios for the same reaction and models as in Fig. 3.

National funded Pythagoras II - EPEAEK II.

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