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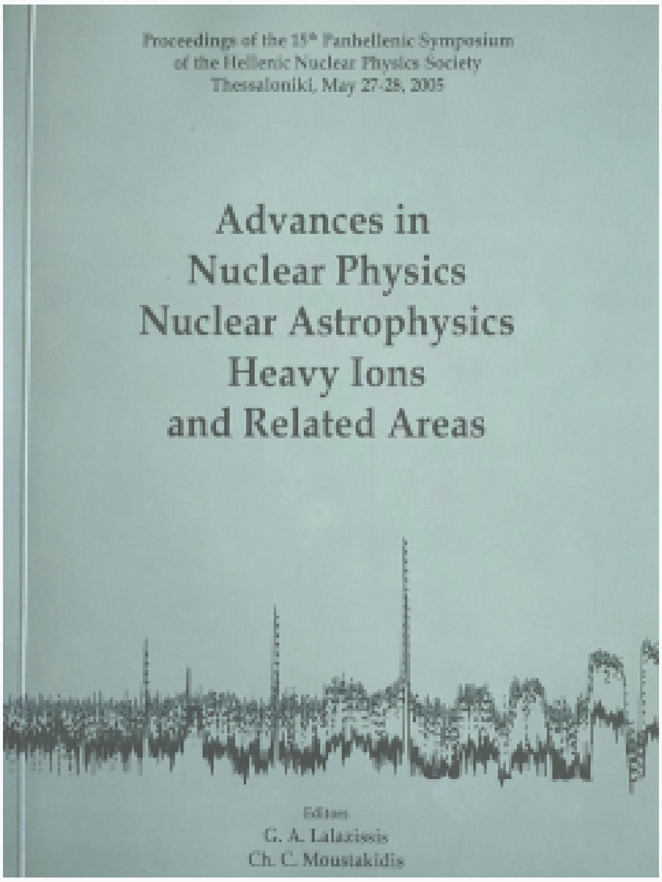

Effects of the in-medium NN cross sections in heavy ion collisions on particle production

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Abstract

The density dependence of the in-medium nucleon-nucleon (NN) cross sections is investigated in terms of particle production in heavy ion collisions (HIC). It is found, in particular, that the in-medium modifications of the *inelastic* NN cross sections considerably affect the pion yields and improve the comparison with experimental information. Such studies are important in determining the still unknown behavior of the nuclear equation of state (EoS) at supra-normal densities in HIC.

1 Introduction

The knowledge of the properties of highly compressed and heated hadronic matter is an important issue for the understanding of astrophysics such as the physical mechanism of supernovae explosions and the physics of neutron stars [1,2]. HIC provide the unique opportunity to explore highly excited hadronic matter, i.e. the high density behavior of the nuclear EoS, under controlled conditions (high baryon energy densities and temperatures) in the laboratory [3]. Important observables have been the nucleon collective dynamics [3,4] and the dynamics of produced particles such as pions and kaons [5]. However, the reaction dynamics is a rather complex process which involves the nuclear mean field (EoS) and binary 2-body collisions. In the presence of the nuclear medium the treatment of binary collisions represents a non-trivial topic. The NN cross sections for elastic and inelastic processes, which are the crucial physical parameters here, are experimentally accessible only for the free space and not for 2-body scattering at finite baryon density. Recent microscopic studies, based on the T-matrix approach, have shown a strong decrease of the elastic NN cross section [6] in the presence of a hadronic medium. These in-medium effects of the elastic NN cross section considerably influence the hadronic reaction dynamics [7]. Obviously the question arises whether similar in-medium effects of the *inelastic* NN cross sections may affect the reaction dynamics and, in particular, the production of particles (pions and kaons). Since microscopic results are not available, we discuss here in a simple phenomenological way possible density modifications of the inelastic NN cross sections and their influences on particle multiplicities.

2 Theoretical background and results

The theoretical description of HIC is based on the kinetic theory of statistical mechanics, i.e. the Boltzmann Equation [8]. The relativistic semi-classical analogon of this equation is the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) equation [9]

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

where $f(x,k^*)$ is the single particle distribution function. In the collision term the short-hand notation $f_i \equiv f(x,k_i^*)$ for the particle and $\tilde{f}_i \equiv (1 - f(x,k_i^*))$ and the hole-distribution is 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 lhs of eq.(1), the drift term, 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 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 in-medium cross sections enter into 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.

In the kinetic equation (1) one should use both physical quantities, the mean field (EoS) and the collision integral (cross sections) according to 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 fields and cross sections have been used. In these models adjusting the known bulk properties of nuclear matter around the saturation point one tries to constrain the models for supra-normal

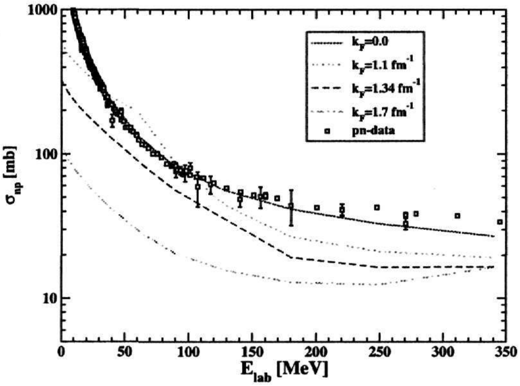

Fig. 1. Elastic in-medium neutron-proton cross sections at various Fermi momenta k_F as function of the laboratory energy E_{lab}. The free cross section ($k_F = 0$) is compared to the experimental total np cross section [6].

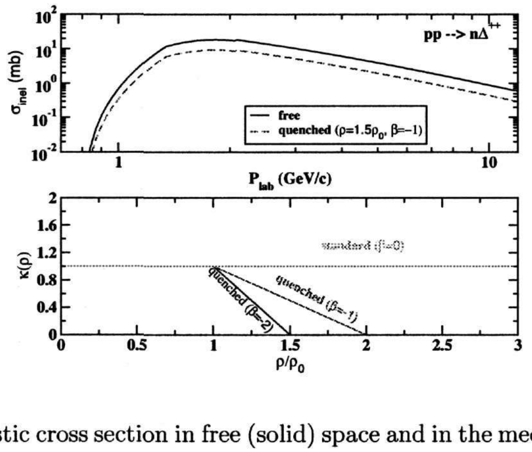

Fig. 2. Top: inelastic cross section in free (solid) space and in the medium ($\rho = 1.5\rho_0$) using $\beta = -1$. Bottom: Density dependence of the quenching function $\kappa(\rho, \beta)$ for different β-values.

densities with the help of heavy ion reactions [10,11]. Medium modifications of the NN cross section are usually not taken into account which works, in comparison to experimental data, astonishingly well [10–13]. However, in particular kinematics regimes a sensitivity of dynamical observables such as collective flow and stopping [7,14] or transverse energy transfer [15] to the elastic NN cross section has been observed.

Fig. 1 shows 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) as found in relativistic Dirac-Brueckner (DB) calculations [6]. The presence of the medium leads to a substantial suppression of the cross section which is most pronounced at low laboratory energy E_{lab} and high densities where the Pauli-blocking of intermediate states is most efficient. At larger E_{lab} asymptotic values of 15-20 mb are reached. However, not only the total cross section but also the angular distributions are affected by the presence of the medium. The initially strongly forward-backward peaked np cross sections become much more isotropic at finite densities [6] which is mainly do to the Pauli suppression of soft modes (π-exchange) and correspondingly of higher partial waves in the T-matrix [6].

Obviously one expects similar in-medium effects for the inelastic NN cross sections mainly due to Pauli-blocking of intermediate scattering states and in-medium modified matrix elements. Such microscopic studies for inelastic processes are very rare or still in development [16,17]. However, to explore the sensitivity we use here a rather simple parametrization which asumes a reduction of the inelastic NN cross section with increasing baryon density, in line with that of Fig. 1 for the elastic one which has previously been used in Ref. [16]. This can be achieved by asuming a factorization of the effective matrix element of the form

$$\overline{|M_{eff}|^2} = \kappa(\rho, \beta)\overline{|M_{vac}|^2} \tag{3}$$

with M_{vac} the vacuum matrix element (taken from experimental free scattering data) and $\kappa(\rho, \beta)$ a density dependent function depending on a quenching parameter β. A very simple parametrization of the function $\kappa(\rho)$ is shown in Fig. 2 (bottom panel) for different values of the parameter β. The effect on the inelastic NN cross section is shown on the top of Fig. 2 for the choice $\beta = -1$. A significant reduction of the effective inelastic NN cross section (by a factor of 2) is observed with respect to that of the free case at a given baryon density $\rho = 1.5\rho_0$.

We have applied this parametrization in the collision intergral of the transport equation (1) and analyzed the transport calculations in terms of particle yields. In Fig. 3 we present the pion yields for a central Au+Au collision at 1 AGeV bombarding energy. The time evolution of the multiplicity of produced Δ-resonances is shown with their maximum arround 15 fm/c which corresponds to the time of maximum compression. Due to the finite lifetime these resonances decay into pions (and nucleons) according $\Delta \longrightarrow \pi N$ (some of these pions are re-absorbed in the inverse process, i.e. $\pi N \longrightarrow \Delta$). This mechanism continues until all resonances have decayd leading to a final constant pion yield for times $t \geq 50$ fm/c (the so-called freeze-out time). After

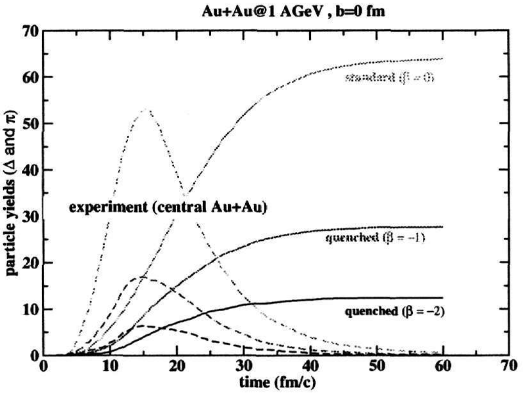

Fig. 3. Time evolution (in units of fm/c) of the multiplicity of Δ-resonances (dashed lines) and pions (solid lines) for different β-values as indicated. The gray band represents the range of experimental data for central Au+Au reactions at 1 AGeV incident energy [18].

the freeze-out the pions can be measured experimentally. The experimental pion multiplicity is schematically shown in Fig. 2 by the gray band for central Au+Au collisions [18]. We observe an essential reduction of the pion multiplicity using the effective inelastic NN cross sections, in line with the previous Fig. 2. As an important result the calculations with the effective inelastic NN cross section describe the experimental data reasonably well for a quenching parameter of about $\beta = -1$.

3 Conclusions

We have investigated the in-medium or density effects of the inelastic NN cross sections on the reaction dynamics on HIC in terms of particle yields such as pions. A significant reduction of the inelastic NN cross section with increasing baryon density turns out to be neccessary in order to fit the experimental pion yields. This in-medium dependence of the inelastic NN cross section is consistent with microscopic studies of the elastic scattering and can thus be motivated microscopically.

For a definitive conclusion further studies are desirable including an analysis of the collective flow of pions as well as including the kaon production. Due to the strong interrelation between the mean field dynamics and the in-medium dependence of the NN cross sections we conclude such studies to be very important in determining the properties of highly compressed and hot hadronic matter.

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