Effect of the K^+ in-medium potential on K^+ production in heavy ion collisions

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Abstract. K^+ meson productions in nucleus-nucleus collisions at energies near the kaon production threshold energy were investigated within the quantum molecular dynamics (QMD) model based on the covariant kaon dynamics. We analyzed the rapidity dependence of the direct flow v_1 and the elliptic flow v_2 of K^+ meson, and the transverse momentum (p_T) dependence of v_1 for the K^+ meson in Ni + Ni collisions at 1.91 AGeV, and compared the results with the FOPI data. We observed that the kaon in-medium potential obviously affects the K^+ production in nucleus-nucleus collisions. After taking into account the K^+ in-medium potential and using the soft equation of state, the theoretical results are in good agreement with the experimental data.

1. Introduction

Relativistic heavy ion collisions at bombarding energies of 1-2 A GeV provide the unique possibility to reach nuclear matter with densities of 2-3 ρ_0. $\rho_0 = 0.16 fm^{-3}$ is the nuclear saturation density. Under the circumstances, the properties of hadrons are modified by many theoretical investigations based on the spontaneously broken chiral symmetry. This modifies the nuclear potential, such as the effect of the surrounding strongly interacting matter on the mass and width of hadrons. K^+ meson production near the production threshold energies in heavy ion collisions is considered to be sensitive to the in-medium modification. Calculations by Zheng *et al.* [1] demonstated that the new FOPI data on the kaon in-plane flow [2] are best described by using the kaon potential $U_k(\rho_0) \approx 30 MeV$ given by the Brown-Rho (BR) parameterization [3].

Here, we present our investigation of the in-medium modificaton of integrated directed flow, elliptic flow using QMD transport calculations with and without the assumption of a K^+ in-medium potential. The in-medium modification of K^+ meson can be fitted by comparing the QMD results with FOPI experimental data.

2. The QMD model

In our model the nuclear system is described by the QMD model [4]. The natural framework to study the interaction between pseudoscalar mesons and baryons at low energies is the Chiral Perturbation Theory (ChPT). In the Chiral Lagrangian equation, the field equations for the $K^{\pm}$–meson are derived from the Euler-Lagrange equations [5]

$$\left[(\partial_\mu \pm iV_\mu)^2 + m_K^{*2}\right]\phi_{K^\pm}(x) = 0. \tag{1}$$

The kaonic vector potential is shown in equation (1)

$$V_\mu = \frac{3}{8f_\pi^*} j\mu, \tag{2}$$

The effective mass m_K^* of the kaon is then given by

$$m_K^* = \sqrt{m_K^2 - \frac{\sum_{KN}}{f_\pi^{*2}}\rho_s + V_\mu V^\mu}, \tag{3}$$

Where $m_K = 0.496$ GeV is the bare kaon mass. Due to the bosonic character, the coupling of the scalar field to the mass term is no longer linear, as for the baryons, but quadratic and contains an additional contribution originating from the vector field. The effective quasi-particle mass defined by equation (3) is a Lorentz scalar and is equal for K^+ and K^-.

The $K^{\pm}$ single-particle energy is expressed as

$$\omega_{K^\pm}(\mathbf{k},\rho) = \sqrt{\mathbf{k}^{*2} + m_K^{*2}} \pm V_0, \tag{4}$$

Where $k^* = k \mp V$ is the kaon effective momentum, $k_\mu = (k_0, \mathbf{k})$, $V_\mu = (V_0, \mathbf{V})$. The kaon vector field is introduced by minimal coupling into the Klein-Gordon with opposite signs for K^+ and K^-. m_K^* is the kaon effective (Dirac) mass. The kaon (antikaon) potential $U_{K^\pm}(\mathbf{k},\rho)$ is defined as

$$U_{K^\pm}(\mathbf{k},\rho) = \omega_{K^\pm}(\mathbf{k},\rho) - \omega_0(\mathbf{k}), \tag{5}$$

$$\omega_0(\mathbf{k}) = \sqrt{\mathbf{k}^2 + m_k^2} \tag{6}$$

In this paper we used the Brown and Rho potential $U_{K^\pm}(\rho_0) \approx 30MeV$. For the nuclear forces we use the standard momentum dependent Skyrme interactions corresponding to a soft equation of state (EOS) (the compression modulus K is 200 MeV) and a hard EOS (the compression modulus K is 380 MeV).

3. Results and Discussions

The rapidity dependence of direct flow for K^+ mesons in Ni + Ni collisions at 1.91 AGeV is given in figure 1. It can be seen from this figure that the calculated results with the K^+N potential are better fitted to the experimental data. Without any in-medium modifications the K^+ mesons should be emitted nearly isotropic i.e., v_1 is close to zero. A repulsive K^+N potential manifests itself by pushing the K^+ mesons away from the protons, thus generation the antiflow signature of K^+ mesons. In a recently paper [6] contributes to a further understanding in this case, they had to link the flow measurements of the K^+ properties the nuclear medium, a comparison to the predictions the hadron string dynamics (HSD) model [7] and isospin quantum molecular dynamics (IQMD) [8] for description kaon dynamics. We calculate the root mean square errors (RMSE) for each value given by using the soft (hard) EOS and with and without the K^+N potential. The results are given in table 1. This table shows the result calculated by using the soft EOS and with K^+N potential has the smallest RMSE, indicating that this result is the best one for describing the FOPI data. This finding is also supported by recent analysis [9] of the two experimental observables which lead to a soft hadronic EoS.

Table 1. The root mean square error (RMSE) for calculated results of v_1 (y_0) of K^+ in Ni + Ni collisions at 1.91 AGeV.

	SW	SWO	HW	HWO
RMSE	0.0170	0.0251	0.0171	0.0324

Figure 2 displays the rapidity dependence of $(v_2\,(y_0))$ for K^+ mesons in Ni + Ni collisions at 1.91 A GeV. It is seen from this figure that the K^+ emissions are observed to elliptic flow move out of plane as indicated by the negative v_2 values and the calculated results with K^+N potential are in better agreement with the FOPI data. The transverse momentum (p_T) dependence of v_1 for K^+ mesons as it nears the target rapidity $(-1.3 < y_0 < -0.5)$ in the peripheral (left) and central (right) collisions in Ni + Ni collisions at 1.91 AGeV is shown in figure 3. This figure illustrates that $v_1\,(p_T)$ of K^+ mesons in peripheral collisions shows a slight stronger p_T dependence then the one in central collisions. This feature can be reasonably observed by our theoretical calculations. From this figure it is known that the calculated results with K^+N potential are in agreement with the data. In peripheral collisions the calculated result by using the soft EOS and with K^+N potential has the smallest RMSE (0.011) and in the central collisions the calculated result, by using the soft EOS and with K^+N potential, has the smallest RMSE (0.003). This indicates that the result calculated by using the soft EOS and with K^+N potential is the best one for describing the experimental data. For the centrality are reasonable with QMD calculations including the in-medium potential, this pattern is agreement with other work [10]. The QMD model reproduced p_T dependence and the strength of the v_1 coefficient for low p_T at $(p_T < 0.4)$ GeV/c. For the peripheral event show a stronger p_T dependence when compared to the centrality.

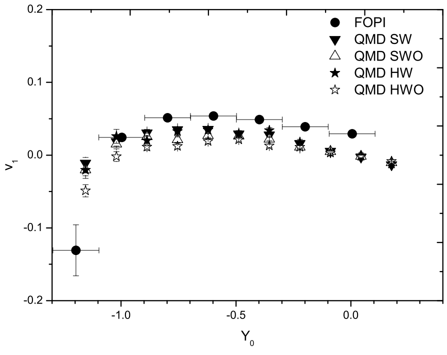

Figure 1. Rapidity dependence of direct flow for K^+ mesons in Ni + Ni collisions at 1.91 AGeV. Full and empty triangles are the calculated results using the soft EOS with and without K^+N potential respectively. Full and empty stars are the calculated results using the hard EOS with and without K^+N potential respectively. Full circles represent the FOPI data [10].

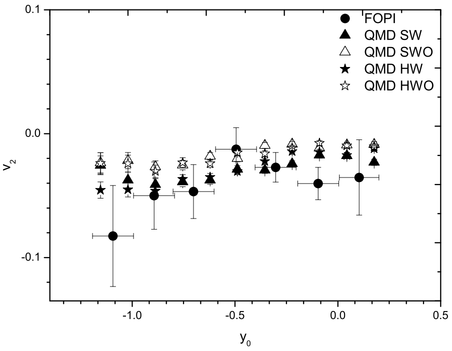

Figure 2. Rapidity dependence of v_2 for K^+ mesons in Ni + Ni collisions at 1.91 A GeV. Full and empty triangles are the calculated results using the soft EOS with and without K^+N potential respectively. Full and empty stars are the calculated results using the hard EOS with and without K^+N potential respectively. Full circles represent the FOPI data [10].

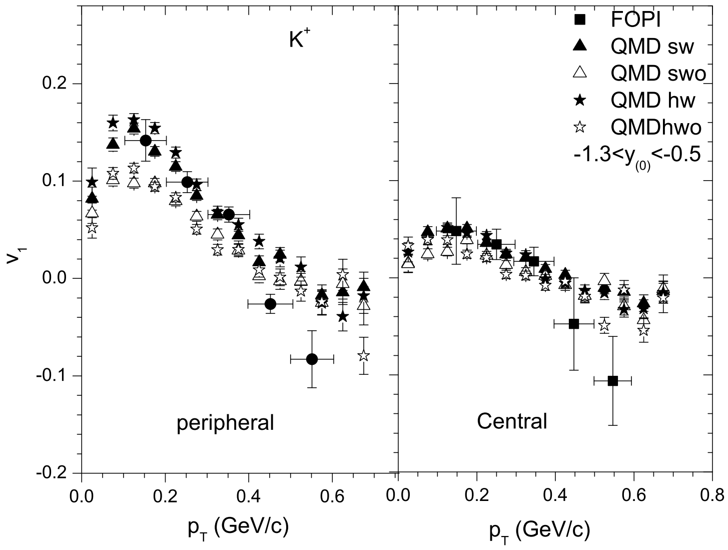

Figure 3. Transverse momentum (p_T) dependence of v_1 for K^+ mesons near target rapidity ($-1.3 < y_0 < -0.5$) in peripheral (left) and central (right) collisions in Ni + Ni collisions at 1.91 AGeV. Full and empty triangles are the results calculated by using the soft EOS with and without K^+N potential respectively. Full and empty stars are the results calculated by using the hard EOS with and without K^+N potential respectively. Full circles represent the FOPI data [10].

4. Conclusions

We used the quantum molecular dynamics model based on the kaon covariant dynamics to simulate the K^+ production in nucleus-nucleus collisions at energies near the kaon production threshold energy, to analyze the rapidity dependence of v_1 and v_2 for K^+ mesons, the transverse momentum dependence of v_1 for K^+ mesons. We observe that after taking into account the K^+ in-medium potential and using the soft equation of state, the theoretical results are in good agreement with the experimental data. The theoretical investigations reproduce corresponding data [6] when K^+N in medium potential are inclued. Concerning the nuclear equation of state is also supported by recent analysis [9, 11, 12] which lead to a soft hadronic EoS.

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