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Kaon Flow in Heavy-Ion Collisions*

ZHENG Yu-Ming CHU Zi-Li
(China Institute of Atomic Energy, Beijing 102413, China)
Fuchs Christian Faessler Amand
(Institut für Theoretische Physik der Universität Tübingen D-72076 Tübingen, Germany)
XIAO Wu HUA Da-Ping
(Graduate School of Nuclear Industry, Beijing 102413, China)

Abstract The kaon flow in heavy-ion collisions at intermediate energy is studied in the QMD model. The calculated results show that the experimental data are only consistent with the ones that include the kaon mean-field potential from the chiral Lagrangian.This indicates that the sideflow pattern of positive charged kaons is an useful probe of the kaon potential in nuclear medium.

Key words heavy-ion collision, the kaon flow, the in-medium kaon potential

The knowledge about in-medium modifications of the kaon properties is important not only to astrophysics but also to nuclear physics.In astrophysics it is related to a possible formation of kaon condensation in neutron stars[1,2]. In nuclear physics the kaon production in heavy ion collisions has attracted much attention. It is found that the kaon yield in heavy ion collisions at subthreshold energies, i.e. below 1.56GeV/nucleon, is sensitive to the nuclear equation of state (EOS) used in the transport model[3−7]. On the other hand, the transverse flow of kaons from heavy ion reactions was suggested to be a good probe of the kaon potential in the nuclear medium[8−11]. This problem, however, is still in debate. It was pointed out[12] that the experimental data can be alternatively described by invoking rescattering effects instead of in-medium kaon potential. Recently, FOPI collaboration[13] published new data with improved precision, which lead to be possible to study further this problem.

In this paper the transverse flow of positive charged kaons (K^+), i.e. the average K^+ in-plane transverse momentum as a function of rapidity, in heavy ion collisions is investigated within the framework of the quantum molecular dynamics (QMD) model[14,15]. For the nuclear EOS we adopt

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soft Skyrme force corresponding to a compression modulus of K=200MeV and with a momentum dependence adjusted to the empirical optical nucleon-nucleus potential[7,14]. The saturation point of nuclear matter is thereby fixed at E_B=−16MeV and ρ_{sat}=0.17fm^{-3}. The calculations include Δ and N*(1440) resonance. The QMD approach with Skyrme interactions contains a controlled momentum dependence and provides a reliable description of the reaction dynamics in the 0.1−2 A GeV energy range[7].

We further consider the influence of an in-medium kaon potential based on effective chiral models[1,7,8,16]. The K$^+$ mean field consists of a repulsive vector part $V_\mu=\frac{3}{8}f_\pi^{*2}j_\mu$ and an attractive scalar part $\Sigma_S=m_K-m_K^*=m_K-\sqrt{m_K^2-(\Sigma_{KN}/f_\pi^2)\rho_S+V_\mu V^\mu}$. Here j_μ is the baryon vector current and ρ_S the scalar baryon density, and Σ_{KN} = 450MeV. Following Ref. [16] in the vector field the pion decay constant in the medium $f_\pi^{*2}=0.6f_\pi^2$ is used. However, the enhancement of the scalar part using f_π^{*2} is compensated by higher order contributions in the chiral expansion[16], and therefore here the bare value is used, i.e. $\Sigma_{KN}\rho_S/f_\pi^2$. Compared to other chiral approaches[8] the resulting kaon dispersion relation shows a relatively strong density dependence. The increase of the in-medium K$^+$ mass $\tilde{m}_K$, Eq. (2), with this parameterization is still consistent with the empirical knowledge of kaon-nucleus scattering and allows one to explore in-medium effects on the production mechanism arising from zero temperature kaon potential. For the kaon production via pion absorption πB →YK$^+$ the elementary cross section of Ref. [17] is used. For the NN→BYK$^+$ channels we apply the cross sections of Ref. [18] which give a good fit to the COSY data close to threshold. For the case of NΔ →BYK$^+$ and ΔΔ→BYK$^+$ reactions experimentally are rare. Thus we rely on the model calculation of Ref. [19]. In the case that a N* resonance is involved in the reaction we used the same cross section as for nucleons. In the presence of scalar and vector fields the kaon optical potential in nuclear matter has the same structure as the corresponding Schrödinger equivalent optical potential for nucleons[20]

$$U_{opt}(\rho,\boldsymbol{p}_K)=-\Sigma_S+\frac{1}{m_K}p_{K\mu}V^\mu+\frac{\Sigma_S^2-V_\mu^2}{2m_K}, \tag{1}$$

and leads to a shift of the threshold conditions inside the medium. To fulfill energy-momentum conservation the optical potential is absorbed into a newly defined effective mass

$$\tilde{m}_K(\rho,\boldsymbol{p}_K)=\sqrt{m_K^2+2m_K U_{opt}(\rho,\boldsymbol{p}_K)}\quad, \tag{2}$$

which is a Lorentz scalar and sets the canonical momenta on the mass-shell $0=p_\mu^2-\tilde{m}_K^2$. Thus, the threshold condition for K$^+$ production in baryon induced reactions reads $\sqrt{S}\geq\tilde{m}_B+\tilde{m}_Y+\tilde{m}_K$ with $\sqrt{S}$ the center-of-mass energy of the colliding baryons. For a consistent treatment of the thresholds the scalar and vector baryon mean fields entering into Eq. (2) are determined from two versions of the nonlinear Walecka model with K = 200MeV[4]. The hyperon field is thereby scaled by 2/3. Since the parameterizations chosen for the nonlinear Walecka model yield the same EOS as the Skyrme ones, the overall energy is conserved. The kaon production is treated perturbatively and generally does not affect the reaction dynamics[4,21]. The rescattering effects and Coulomb interactions of kaons are also included.

In our calculation we have used an impact parameter cut of $b<3\,\mathrm{fm}$, corresponding to the chosen centrality in the experiment, and a p_t cut of $p_t/m>0.5$, which is in agreement with the experimental acceptance[9].

Fig. 1 shows the average K^+ in-plane transverse momentum, $\langle p_x \rangle /m$ (Here m is the kaon mass in free space.), as a function of scaled rapidity ($Y^{(0)} = Y_{lab}/Y_{CM} - 1$) in 1.93 A GeV $^{58}Ni+^{58}Ni$ reactions. In the figure the full squares represent old experimental data[9]. The full circles stand for new data[13], their reflections with respect to mid-rapidity are shown by the open circles. The full down (up) triangles denote the calculated results with (without) kaon potential in the nuclear medium. The connective lines among calculated points are to guide the eye. It is seen clearly from

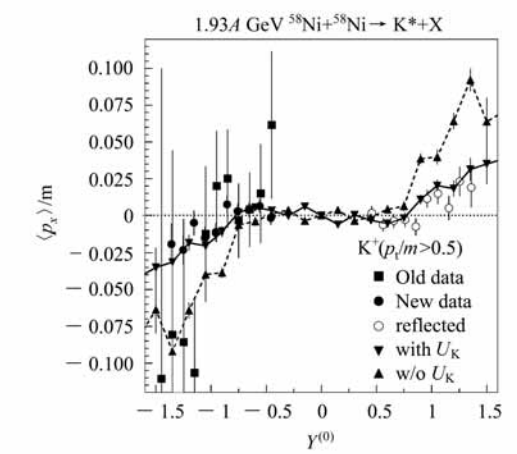

Fig. 1. The sideflow of K^+ as a function of scaled rapidity ($Y^{(0)} = Y_{lab}/Y_{CM} - 1$) in 1.93 A GeV $^{58}Ni + ^{58}Ni$ reactions. The full squares represent old experimental data[9]. The full circles stand for the new data[13], their reflections with respect to mid-rapidity are shown by the open circles. The full down (up) triangles denote the calculated results with (without) kaon potential in the nuclear medium. The connective lines among calculated points are to guide the eye.

this figure that the theoretical results both with and without kaon potential lie within the error bars of the old data, and can reproduce the nearly vanishing sideflow signal of K^+ mesons. However, the new data with much smaller statistical error bars are only in agreement with the ones that include the kaon potential in nuclear medium. This means that it is necessary to include the kaon potential in nuclear medium in order to describe the new experimental data for the transverse flow of K^+ s.

In summary, we have investigated the transverse flow of K^+s in heavy ion collisions at intermediate energy within the framework of the QMD model. It is found that the new data with improved statistical errors given by FOPI collaboration are consistent with the results that include the kaon mean-field potential from the chiral Lagrangian but not the ones without any potential. This indicates that the transverse flow pattern of kaons is sensitive to the kaon potential in nuclear medium and is an useful probe of the kaon potential in nuclear medium.

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重离子碰撞中的K介子流*

郑玉明　储自立

（中国原子能科学研究院 北京 102413）

Fuchs Christian　Faessler Amand

(Institute of Theoretical Physics, Tuebingen University, Germany)

肖武　华大平

（中国核工业研究生部 北京 102413）

摘要　用量子分子动力学(QMD)模型研究了中能重离子碰撞中的K^+介子流．计算结果显出，实验数据只能与计入由手征拉格朗日导出的K^+平均场势的结果相符合．这表明，K^+介子边流的形式是对在核介质中K^+位势的一个有效的探针．

关键词　重离子碰撞　K介子流　在介质中的K^+位势

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