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Collective flow of K^+ mesons in heavy-ion collisions predicted by the covariant Kaon dynamics*

XING Yong-Zhong(邢永忠)[1)] DAI Yue-Qian(戴月茜)

Institute of Fundamental Physics, Tianshui Normal University, Tianshui 741000, China

Abstract: The directed and elliptic flow of positively charged kaons produced in $^{58}_{28}$Ni+$^{58}_{28}$Ni reactions at incident kinetic energy 1.91 AGeV are studied within the covariant kaon dynamics and compared to new data. We observe that the influence of the Lorentz force on the directed and differential directed flow of K^+ mesons is obvious. Our calculated results indicate that it is necessary for the Lorentz force to be included in the kaon dynamics in order to reasonably describe experimental data.

Key words: kaon meson, collective flow, heavy-ion collisions, covariant dynamics

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1 Introduction

Kaon meson production in heavy ion reactions at intermediate energies has been one of the widely interesting topics in nuclear physics for the past several decades since it opens the possibility to explore several fundamental questions, which are also very important in particle physics and astrophysics [1–6]. K^+ meson is produced in the early stage of heavy ion collisions at which the nuclear density in the reaction zone is much higher than the saturation density ($\rho_0=0.16$ fm^{-3}). After the productions K^+ mesons escape near-freely from the reaction zone due to the relatively low K^+N scattering cross section (~10 milibarn) and the absence of the absorption channel of a K^+ meson on a nucleon in the strong interaction. So, kaon production is proposed to be a sensitive probe to study the nuclear equation of state (EoS) in dense hadronic matter [7]. In 2002, P. Danielewicz et al. [8] presented an EoS constrained by the flow data of heavy ions and kaons, which causes wide attention. Meanwhile they also stated that it is impossible to find a unique formulation of the EoS to reproduce all experimental data. Other published experimental analysis and transport calculations come to similar conclusions [9, 10]. Recently, Reisdorf [11] made great efforts to complement earlier data by systematic investigations encompassing a large range of system energy and the large acceptance apparatus (FOPI) at the SIS accelerator. They [12] reported results of the simultaneous measurements of kaon and antikaon meson in Ni+Ni collisions at an incident beam energy of 1.91 AGeV, which is close to the various strangeness production threshold energy. These newly-delivered experimental data provide us with a chance to enrich our knowledge of the complicated dynamical processes and to improve the existing theoretical model.

As is already known [13–15], the combination of Quantum Molecular Dynamics (QMD) with covariant kaon dynamics, in which a Lorentz-like force can be derived for the kaon meson inside the nuclear medium, is one of the successful theoretical transport models for simulating K^+ meson production in heavy ion collisions at the SIS energy region. With this model the collective flow of K^+ meson and some associated produced particles have been reproduced reasonably well [15–17]. Naturally, the question arises of whether this model can also describe the collective flow of K^+ produced in this reaction. Alternatively, can the covariant kaon dynamics model reproduce the newly released experimental data? To answer this question, we present here the theoretical calculations within the covariant kaon dynamics and compare our calculated results to the new data. In the following we first review briefly the theoretical model, then give our results and discussions.

2 The model

In the QMD model [13, 18, 19] each nucleon is represented by a coherent state of the form (we set $\hbar$, c=1)

$$\psi(\vec{r},\vec{p}_0,t)=\frac{\exp[\mathrm{i}\vec{p}_0\cdot(\vec{r}-\vec{r}_0)]}{(2\pi L)^{3/4}}\mathrm{e}^{-(\vec{r}-\vec{r}_0)^2/4L}, \tag{1}$$

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1) E-mail: yzxing@tsnc.edu.cn

where $\vec{r}_0$ is the time-dependent center of the Gaussian wave packet in coordinate space. The width L is kept constant, which means that one does not allow the spreading of the wave function. Otherwise, the whole nucleus would spread in coordinate space as a function of time. L is set to be L=1.08 fm^2 corresponding to a root mean square radius of the nucleon of 1.8 fm. To keep the formulation as close as possible to the classical transport theory, one uses Wigner density instead of working with wave function. The Wigner representation of our Gaussian wave packets obeys the uncertainty relation $\Delta r_x \Delta p_x = \hbar/2$.

The time evolution of the N-body distribution is determined by the motion of the centroids of the Gaussians (r_{i0}, p_{i0}), which are propagated by the Poisson brackets

$$\dot{\vec{p}}_{i0}=\{\vec{r}_{i0},H\} \quad \dot{\vec{r}}_{i0}=\{\vec{p}_{i0},H\}, \tag{2}$$

where H is the nuclear Hamiltonian

$$H=\sum_i \sqrt{{\boldsymbol{p}_{i0}}^2+m_i^2}+\frac{1}{2}\sum_{i\neq j}(U_{ij}^{\rm str}+U_{ij}^{\rm cou}). \tag{3}$$

Here $U_{ij}^{\rm str}$ is the nuclear mean field and $U_{ij}^{\rm cou}$ is the Coulomb interaction.

The natural framework to study the interaction between pseudoscalar mesons and baryons at low energies is chiral perturbation theory (ChPT). From the chiral Lagrangian the field equation for the $\mathrm{K}^{\pm}$–meson is derived from the Euler-Lagrange equations [13, 19]:

$$\left[\partial_\mu\partial^\mu \pm \frac{3\mathrm{i}}{4f_\pi^{*2}}j_\mu\partial^\mu+\left(m_{\rm K}^2-\frac{\Sigma_{\rm KN}}{f_\pi^{*2}}\rho_{\rm s}\right)\right]\phi_{\rm K^\pm}(x)=0. \tag{4}$$

Here the mean field approximation has already been applied. In Eq. (4) $\rho_{\rm s}$ is the baryon scalar density, j_μ is the baryon four-vector current, f_π^* is the in-medium pion decay constant. Introducing the kaonic vector potential

$$V_\mu=\frac{3}{8f_\pi^{*2}}j_\mu, \tag{5}$$

Eq. (4) can be rewritten in the form [14]

$$\left[(\partial_\mu \pm \mathrm{i}V_\mu)^2+m_{\rm K}^{*2}\right]\phi_{\rm K^\pm}(x)=0. \tag{6}$$

Thus, the vector field is introduced by minimal coupling into the Klein–Gordon equation. The effective mass $m_{\rm K}^*$ of the kaon is then given by [15, 21]

$$m_{\rm K}^*=\sqrt{m_{\rm K}^2-\frac{\Sigma_{\rm KN}}{f_\pi^{*2}}\rho_{\rm s}+V_\mu V^\mu}, \tag{7}$$

where $m_{\rm K}$=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 Eq. (7) is a Lorentz scalar and is equal for K^+ and K^-.

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

$$\omega_{\rm K^\pm}(\boldsymbol{k},\rho)=\sqrt{\boldsymbol{k}^{*2}+m_{\rm K}^{*2}}\pm V_0, \tag{8}$$

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

$$U_{\rm K^\pm}(\boldsymbol{k},\rho)=\omega_{\rm K^\pm}(\boldsymbol{k},\rho)-\omega_0(\boldsymbol{k}), \tag{9}$$

where

$$\omega_0(\boldsymbol{k})=\sqrt{\boldsymbol{k}^2+m_{\rm K}^2}. \tag{10}$$

In nuclear matter at rest the spatial components of the vector potential vanish, i.e. $\boldsymbol{V}=0$, and Eq. (6) reduces to the expression already given in Ref. [20]. The kaon (antikaon) potential $U_{\rm K^\pm}(\boldsymbol{k}, \rho)$ then reduce to the form

$$U_{\rm K^\pm}(\boldsymbol{k},\boldsymbol{V}=0,\rho) = \sqrt{\boldsymbol{k}^2+m_{\rm K}^2-\frac{\Sigma_{\rm KN}}{f_\pi^{*2}}\rho_{\rm s}+V_0^2} \pm V_0-\sqrt{\boldsymbol{k}^2+m_{\rm K}^2}. \tag{11}$$

The covariant equations of motion are obtained in the classical (test particle) limit from the relativistic transport equation for the kaons which can be derived from Eq. (6). They are analogous to the corresponding relativistic equations for baryons and read [13, 15]

$$\frac{\mathrm{d}q^\mu}{\mathrm{d}\tau}=\frac{k^{*\mu}}{m_{\rm K}^*}, \quad \frac{\mathrm{d}k^{*\mu}}{\mathrm{d}\tau}=\frac{k_\nu^*}{m_{\rm K}^*}F^{\mu\nu}+\partial^\mu m_{\rm K}^*. \tag{12}$$

Here $q^\mu=(t,\boldsymbol{q})$ are the coordinates in Minkowski space and $F^{\mu\nu}=\partial^\mu V^\nu-\partial^\nu V^\mu$ is the field strength tensor for K^+. For K^- the vector field changes sign. The equations of motion are identical, $F^{\mu\nu}$ has to be replaced by $-F^{\mu\nu}$. The structure of Eq. (12) may become more transparent considering only the spatial components

$$\frac{\mathrm{d}\boldsymbol{k}^*}{\mathrm{d}t}=-\frac{m_{\rm K}^*}{E^*}\frac{\partial m_{\rm K}^*}{\partial \boldsymbol{q}}\mp\frac{\partial V^0}{\partial \boldsymbol{q}}\pm\frac{\boldsymbol{k}^*}{E^*}\times\left(\frac{\partial}{\partial \boldsymbol{q}}\times\boldsymbol{V}\right), \tag{13}$$

where the upper (lower) signs refer to K^+ (K^-). The term proportional to the spatial component of the vector potential gives rise to a momentum dependence which can be attributed to a Lorentz force, i.e. the last term in Eq. (13). Such a velocity-dependent ($\boldsymbol{v}=\boldsymbol{k}^*/E^*$) Lorentz force is a genuine feature of relativistic dynamics as soon as a vector field is involved.

For the nuclear force we use the standard momentum-dependent Skyrme interaction corresponding to a soft EoS (the compression modulus K is 200 MeV). For the determination of the kaon mean field we adopt the corresponding covariant scalar–vector description of the nonlinear $\sigma\omega$ model. Here we use the parametrization of Refs. [22, 23] which corresponds to identical soft nuclear EoSs. The shift of the production thresholds of the kaon by the in-medium potentials is taken into account as described in Refs. [21, 24]. The hyperon fields are scaled according to SU(3) symmetry.

Following Ref. [14], we use the Brown & Rho parameterization (BRP): $\Sigma_{\rm KN}$=450 MeV, f_π^{*2}=$0.6f_\pi^2$ for the vector field and f_π^{*2}=f_π^2 for the scalar part given by $-\Sigma_{\rm KN}/f_\pi^{*2}\rho_{\rm s}$. This scenario accounts for the fact that the enhancement of the scalar part using f_π^{*2} is compensated by higher-order corrections in the chiral expansion [2, 4]. Up to saturation density the Brown and Rho potential is $U_{\rm K^+}(\rho_0)\approx 30$ MeV. For comparison a weaker potential with $\Sigma_{\rm KN}=350$ MeV and the pion decay constant f_π^{*2}=f_π^2 is also applied. This parameterization is called the Ko and Li (KLP) [20], which corresponds to the kaon potential $U_{\rm K^+}(\rho_0)\approx$5 MeV at saturation nuclear density.

3 Results and discussions

In Fig. 1 we show the directed flow (v_1) of $\rm K^+$ mesons as a function of the rapidity $Y^{(0)}$ from $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV for impact parameter b=3.9 fm. In the figure the line with solid diamonds indicates the experimental data[12], the curve with solid circles (hollow circles) stands for the prediction of the covariant kaon dynamical model with BRP(KLP). The curve with solid triangles (hollow triangles) represents the results of the QMD model with static kaon potential, i.e., without the Lorentz forces, which is incovariant for the kaon motion equation with BRP(KLP).

From this figure we can see that (1) the covariant kaon dynamics can reproduce the data in which the Lorentz force (LF) plays an essential role in determining the $\rm K^+$ directed flow, no matter whether the KLP or BRP parameterization scheme is taken into account in the covariant kaon dynamics. This feature indicates, as was concluded in Ref. [14] by evaluating the transverse flow $\langle p_x/m_k\rangle$, that the effect of the LF contribution in the covariant kaon dynamics pulls the kaons back to the spectator matter; (2) covariant kaon dynamics with BRP parameterization give a more reasonable pattern for the $\rm K^+$ directed flow, since there are discrepancies in the cases of BRP and KLP when the same evolution equation is taken. Comparatively, the results with BRP are slightly higher than those with KLP. In view of the distinction induced by various parameterization scenarios being subtle, we omit the results calculated with KLP in the following figures and concentrate our attention on the influence of the Lorentz-like force.

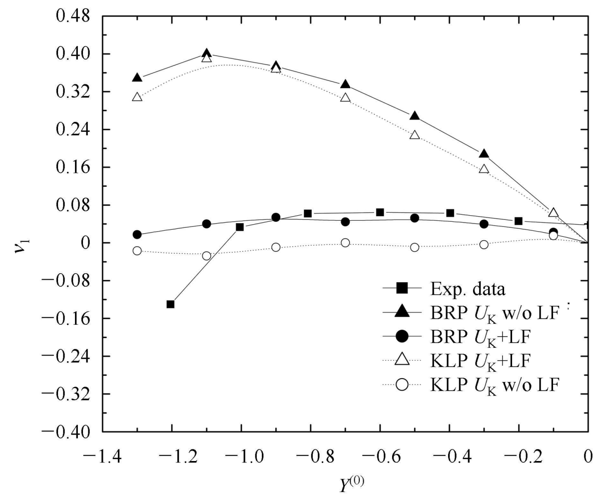

Fig. 1. Directed flow (v_1) of $\rm K^+$ mesons as a function of the rapidity $Y^{(0)}$ from $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV. Theoretical results are obtained for impact parameter b=3.9 fm.

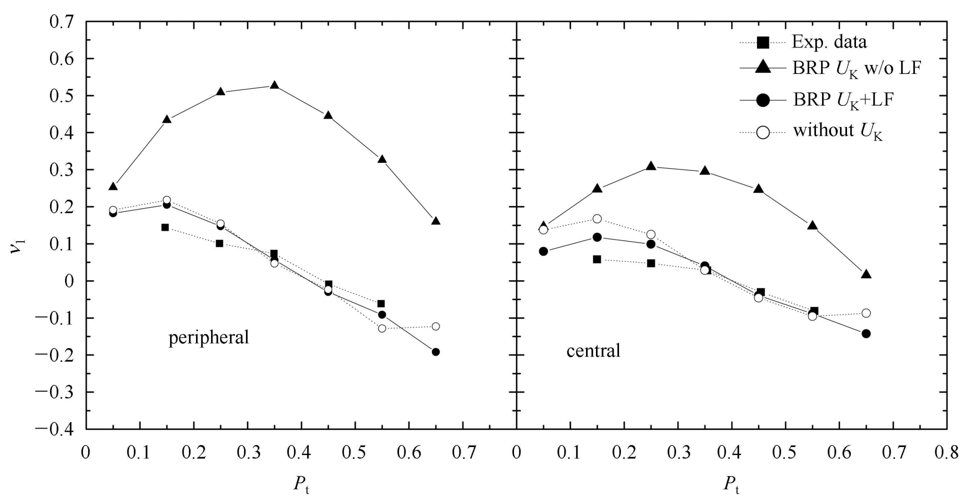

Fig. 2. Different direct flows of $\rm K^+$ in $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV with impact parameters $b=4.95$ fm (peripheral) and b=2.11 fm (central).

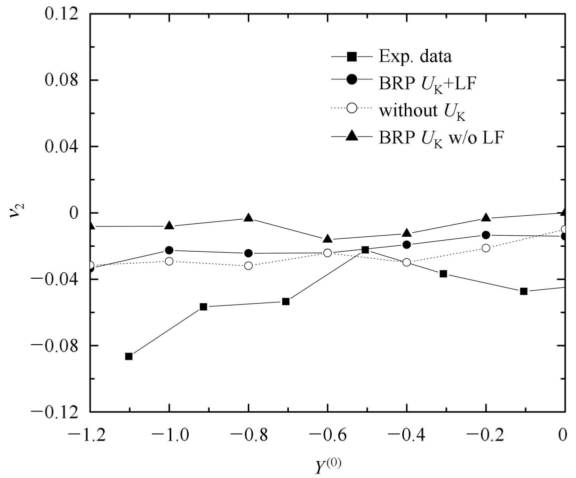

Fig. 3. Rapidity dependence of elliptic flow of the K^+ mesons in $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV.

The different direct flow of K^+ mesons in $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV with impact parameters $b = 4.54$ fm (peripheral) and $b = 2.11$ fm (central) is given in Fig. 2. The dotted curves with hollow circles is the different directed flow of the K^+ mesons produced in the reaction without the kaon final interaction (U_K). The other curves are the same as those shown in Fig. 1. It is seen that the curves with BRP U_K+LF and without U_K are close to each other. This tells us that the Lorentz force counterbalances the repulsive interaction of the K^+ meson, resulting in being comparable to the data. Therefore, the Lorentz force the same as a vector field is also a crucial ingredient in determining the different directed flow of the K^+ mesons.

The rapidity dependence of elliptic flow of the K^+ mesons in $^{58}_{28}$Ni+$^{58}_{28}$Ni collisions at 1.91 AGeV is plotted in the Fig. 3. The indicators of the curves are the same as the ones in Fig. 2. As shown in Fig. 3 of Ref. [12], by comparing the predictions of IQMD and HSD, the out-plane-flow V_2 is not sensitive to the kaon final state interaction. This property is also demonstrated in the results of the covariant kaon dynamics model.

In summary, in the present work the directed and elliptic flows of positively charged kaons produced in $^{58}_{28}$Ni+$^{58}_{28}$Ni reaction at incident kinetic energy 1.91 AGeV are evaluated within the covariant kaon dynamics model combined with the quantum molecular dynamics model and compared to new data. We observe that the influence of the Lorentz force on the directed and differential directed flow of K^+ mesons is obvious. Our calculated results indicate that it is necessary to include the Lorentz force in the kaon covariant dynamics in order to reasonably describe the newly-delivered experimental data. The sensitivity of the directed and differential directed flow of K^+ mesons on the Lorentz force can be used to attribute information on the presence of Lorentz force.

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