Anisotropy of Subthreshold K^+ Emission in Heavy Ion Reactions

Z. S. Wang, Amand Faessler, C. Fuchs, V. S. Uma Maheswari, and D. Kosov
Institut für Theoretische Physik der Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
(Received 27 June 1997)

The origin of the forward-backward enhancement of K^+ emission observed in symmetric nucleus-nucleus collisions at 1 GeV/nucleon has been explored. The nonisotropic pion-baryon reaction leading to K^+ production has been found to play a substantial role in creating the forward-backward peak of the kaon angular distribution. By an analysis including also the effects from relevant final-state interactions on kaons, we can reproduce the experimental kaon angular distribution. We argue that the observed nonisotropic kaon emission may provide a support to the pion-induced channel for subthreshold kaon production in heavy ion reactions. [S0031-9007(97)04562-6]

PACS numbers: 25.75.Dw, 13.75.Jz

Kaon production in heavy ion reactions has been a topic of high interest in physics for a long time. Because of strangeness conservation, K^+ mesons experience little reabsorption, and therefore may provide information on the hot and dense nuclear matter created in the reaction [1,2]. Kaons produced in heavy ion reactions also act as a unique tool for investigating possible modifications of kaon properties in nuclear matter [3–5]. For a long time, the kaon emission had been thought to be isotropic in the *NN* center-of-mass system [6,7]. However, a recent measurement at the Gesellschaft für Schwerionenforschung has found that the kaon angular distribution exhibits a forward-backward peak in the *NN* system for symmetric heavy ion reactions at 1.0 GeV/nucleon [8]. An isotropic kaon distribution can be emitted by a single equilibrated source. However, the elementary hadron-hadron collisions creating kaons occur in the very early stage of the reaction when the equilibrium is far from established in the reaction system. An isotropic preequilibrium kaon emission had been also expected, since kaons had been conventionally assumed to be produced from the reaction $B + B \rightarrow B + K^+ + Y$ (here B denotes a nucleon or a Δ resonance, while Y denotes a Λ or Σ hyperon), which was found experimentally to be nearly isotropic for the *NN* channel, and since kaons had been assumed to interact little with the nuclear medium due to its long mean free path ($\sigma_{KN} \sim 10$ mb). From this point of view, the observed anisotropy might be a signature for the onset of novel kaon production mechanisms, including contributions from higher order partial waves, or for the importance of final-state interactions for the kaons produced. In our previous paper [9], a new kaon production channel, the $\pi + B \rightarrow Y + K^+$ reaction, was found to also be important for incident energies of 1–2 GeV/nucleon and for large nuclear systems. It is well known that the π-induced reaction has a substantial P-wave component which results in a large anisotropy [10]. On the other hand, the final-state interactions such as the K-N elastic rescattering [11], the in-medium kaon potentials of the Coulomb interaction [12], and the strong interaction [3,4] also have observable effects. In this paper, we will explore the effect of the new production channel and the final-state interactions on the kaon angular distribution for symmetric heavy ion reactions at 1 GeV/nucleon.

Here we adopt the framework of the QMD (quantum molecular dynamics) model to describe heavy ion reactions. A soft momentum-dependent nuclear mean field is used throughout this paper. The kaon degrees of freedom are treated in a perturbative way. Kaons are produced via either the conventional BB channel or the novel πB channel. For the first channel, we use a theoretical cross section based on the one-boson-exchange model [13] which was found to be in good agreement with the new data from the COSY-11 collaboration [14]. The angular distribution of this channel is assumed to be isotropic since the data for the reaction $N + N \rightarrow N + Y + K^+$ show no significant anisotropy [15]. A calculated cross section based on a resonance model which can reproduce the data is adopted for the pion-induced channel [16]. In fact, a parametrization of the angular distribution of this channel had been given by Cugnon and Lombard [17] which fitted the observed ratio of forward over backward kaon emission from the pion-induced reaction. In this paper, we present a new parametrization by requiring a correct ratio of forward-backward over sideward emission which we define as

$$C = \frac{\int_{\theta=0^0}^{\theta=60^0} \frac{d\sigma}{d\Omega}\, d\Omega + \int_{\theta=120^0}^{\theta=180^0} \frac{d\sigma}{d\Omega}\, d\Omega}{\int_{\theta=60^0}^{\theta=120^0} \frac{d\sigma}{d\Omega}\, d\Omega}. \qquad (1)$$

Since we concentrate on symmetric heavy ion reactions in which the clear forward or backward emission of the elementary process would be washed out, we have assumed in this paper a forward-backward symmetric angular distribution for the pion-induced reaction as $d\sigma/d\Omega \sim (1 - x \sin\theta)$, where the coefficient x is determined from the factor C extracted from the data (the asymmetry factor C is defined so that $C = 1$ for a spherical distribution of the kaons). This parametrization assures that one evaluates correctly the contribution of the π-induced channel to the forward-backward peak of the kaon angular distribution. In Fig. 1 we present the asymmetry factor C extracted from the data [10] as well as our parametrization.

From the figure, one sees a nontrivial anisotropy in the π-induced reaction, in particular, the reaction involving Λ's. This reaction is more important for subthreshold kaon production due to its lower energy threshold than the one involving the Σ's. In this paper, we use an isospin-averaged angular distribution for the π-induced reaction which has been constructed based on the above parametrization.

After production, a kaon propagates through the nuclear medium and encounters final-state interactions. They are the elastic rescattering of kaons by nucleons, the kaon in-medium mean-field potential of the strong interaction, and the Coulomb interaction of kaons with protons, charged nucleonic resonances, and charged pions. We adopt an empirical kaon strong potential obtained from the impulse approximation which is very similar to the potential suggested recently by Brown and Rho [18] based on chiral perturbation theory. The details of the treatment of the kaon Coulomb and strong interaction potential in the QMD model can be found in Ref. [12].

In Fig. 2 we show the influence of these effects on the kaon angular distribution for the reaction Au + Au at 1 GeV/nucleon and at impact parameter $b = 5$ fm. As expected, an isotropic kaon emission is found with the isotropic BB and πB channels and with no interaction of the kaons with the spectators. The kaon rescattering with the spectators results in a forward-backward peak in the kaon angular distribution, which coincides with the finding in Refs. [8,11]. However, the kaon Coulomb and strong potential have a negligibly small effect. We note that for π^+'s a focusing effect had been found towards $\theta_{cm} = 90°$ due to the Coulomb field generated by spectators of the projectile and target which move relative to each other [19]. A similar effect seems to exist for K^+'s which is, however, much less pronounced due to the larger mass of the K^+ mesons. The trivial effect from the kaon strong potential, which is also repulsive for K^+, can also be understood because this effect occurs essentially in the fireball and has little connection with the spectators, where the nuclear density is much lower than in the fireball. From the figure, one can see clearly that the nonisotropic π-induced channel enhances the forward-backward peak substantially. This is both due to the sizeable contribution of the π-induced channel and due to the nonequilibrium of the reaction system where kaons are produced. In Ref. [9], it was found that in the reaction Au + Au at 1 GeV/nucleon the πB channel produces even more kaons than the BB channel. At higher bombarding energies this channel becomes less important due to its resonancelike energy dependence. On the other hand, the πB collisions which are violent enough for kaon production at the subthreshold beam energy of 1 GeV/nucleon are far from being randomized in momentum space. They distribute mainly parallel to the beam direction and, therefore, lead to a forward-backward enhanced kaon emission. One can also understand the fact that this effect gets much smaller at higher incident energies as observed by Cugnon and Lombard [17] for 2.1 GeV/nucleon and by Li and Ko [20] for alternating-gradient synchrotron energies, since the πB collisions become less important on one hand and more randomly distributed on the other. This coincides with the experimental finding of an approximately isotropic kaon angular distribution in the NN frame at higher incident energies [21]. We notice that there may be an additional effect concerning the π-induced channel. Since it is in essence a secondary process, it may produce kaons away from midrapidity. This may also contribute to the nonisotropic

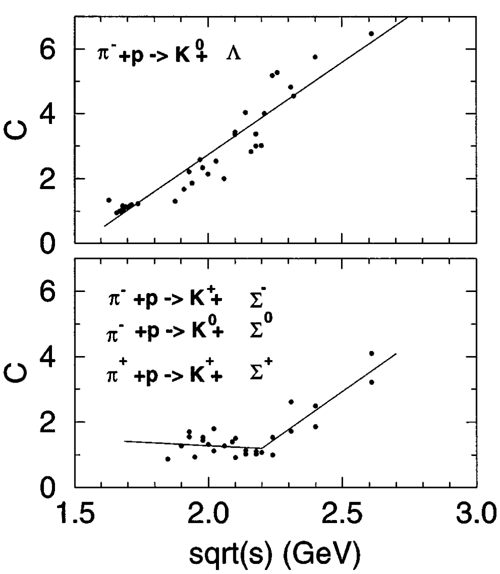

FIG. 1. The asymmetry factor C defined in Eq. (1) for the π-induced reaction. The circles are extracted from experimental data [10] while the lines indicate the parametrizations used in the present paper.

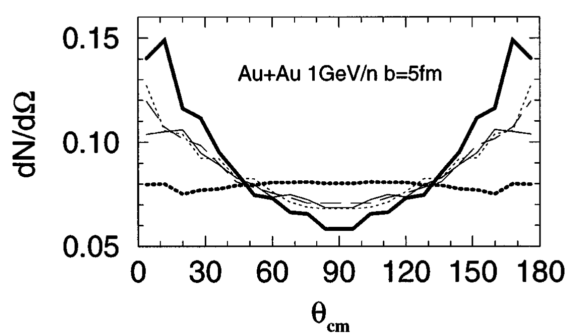

FIG. 2. The K^+ center-of-mass (c.m.) angular distribution obtained by the QMD calculations in different cases, namely, (1) with neither kaon final-state interaction nor the anisotropy of the πB channel (dark dotted line); (2) with only the K-N rescattering (light dotted line); (3) including, in addition, the kaon Coulomb interaction (long dashed line); (4) adding to (3) also the kaon strong potential (light solid line); (5) in addition to (4) including here the nonisotropic $\pi + B \rightarrow K^+ + Y$ channel (dark solid line). All these distributions have been normalized to the total kaon multiplicity.

kaon emission. Our QMD model has included this effect naturally.

In Fig. 3 we present the QMD results of the kaon angular distribution obtained by averaging over impact parameters for the reaction Au + Au at 1 GeV/nucleon. Also shown is the function of $(1/3 + \cos^2\theta)$ which was obtained by fitting the experimental data at different angles of $\theta_{\rm lab} = 44°$, 85°, and 125° in a one-source model [8]. It can be seen that the kaon final-state interactions, which are essentially the K-N rescattering, lead to a forward-backward peaked angular distribution which is insufficient to reproduce the data. This finding is in agreement with Ref. [8]. The π-induced channel, including a nontrivial P-wave contribution, enhances the forward-backward peak substantially since, at this subthreshold beam energy, the energetic πB collisions are not distributed randomly in momentum space. The resultant kaon angular distribution is closer to the experimental result. To see how the theory agrees with experiment we compare, in Fig. 4, directly to the measured kaon momentum spectra at different angles of $\theta_{\rm lab} = 44°$, 85°, and 125°. We note that the kaon cross sections obtained in the present paper are lower than our previous results [9] since we have adopted here a smaller calculated cross section for the BB channel rather than the parametrization given by Randrup and Ko [15]. Since we concentrate in this paper on the kaon angular distribution, we have renormalized the theoretical results with a common factor of 2 as we compare the experimental momentum spectra at different angles. One can see that the data at all three angles can be reproduced simultaneously by the full calculation, including all the effects mentioned above, after renormalizing the theoretical results with a common factor of 2. This means that our calculation can reproduce, apart from a common factor, the measured angular distribution within the error bars for the three angles. On the other hand, it is clear from the figure that the experimental distributions for the different angles fall closer to each other than the theoretical results including only the kaon final-state interactions. In other words, the observed anisotropy in the kaon angular distribution has been underestimated by dropping the nonisotropic πB channel. Therefore, the observed nonisotropic kaon emission may reflect the important role played by the π-induced channel in subthreshold kaon production in heavy ion reactions. It is also necessary to make clear the contribution from the ΔN and $\Delta\Delta$ channels, since they also include some P-wave contribution. However, the $\Delta + N \rightarrow K^+ + Y + N$ or $\Delta + \Delta \rightarrow K^+ + Y + N$ reaction produces a kaon which would occupy the phase space much more randomly than that produced from the $\pi + N \rightarrow K^+ + Y$ reaction, since the former reaction has more particles in the outcoming state. In fact, the BB reaction also has a more symmetric incoming state. By these simple considerations, we believe that the ΔN or $\Delta\Delta$ reaction would exhibit an angular distribution much more isotropic than that of the πN reaction. Therefore, we attribute the observed nonisotropic kaon emission essentially to the π-induced reaction.

Figure 5 shows the dependence of the nonisotropic kaon emission on the impact parameter for the same reaction as in Fig. 4. The factor $F_{\rm peak}$ shown in the figure is a measure of the enhancement of forward-backward kaon emission, which is defined as

$$F_{\rm peak} = \int_{\theta=0°}^{\theta=60°} \frac{dN}{d\Omega}\, d\Omega + \int_{\theta=120°}^{\theta=180°} \frac{dN}{d\Omega}\, d\Omega - \int_{\theta=60°}^{\theta=120°} \frac{dN}{d\Omega}\, d\Omega\,, \quad (2)$$

where $dN/d\Omega$ is the normalized angular distribution. In the case of an isotropic distribution, $F_{\rm peak} = 0$. It can be seen from the figure that the contribution from the nonisotropic π-induced reaction stays more or less unchanged with increasing impact parameters, while the

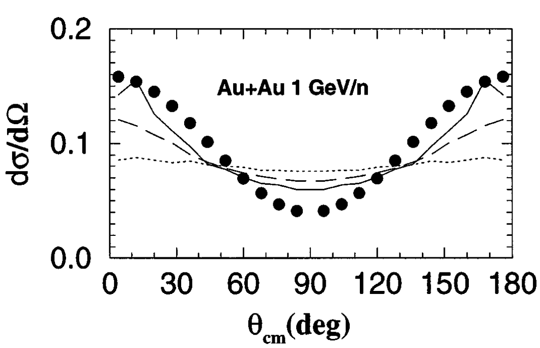

FIG. 3. The K^+ c.m. angular distribution. The lines are the QMD results obtained by integrating over the impact parameters. The dotted, dashed, and solid lines correspond to the cases (1), (4), and (5) in Fig. 2, respectively. The circles denote the function $(1/3 + \cos^2\theta)$ fitted to the experimental data [8]. All of these distributions have been normalized to the total kaon cross section.

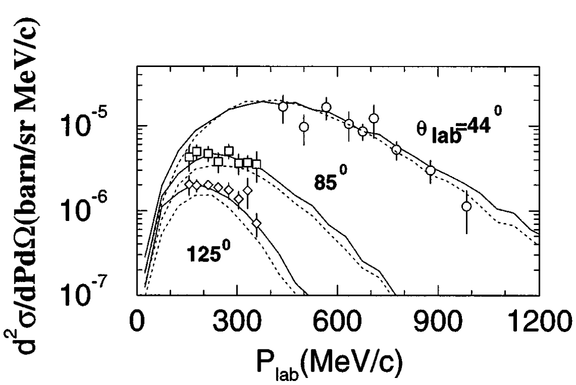

FIG. 4. The K^+ cross section as a function of the momentum in the reaction Au + Au at 1 GeV/nucleon. The circles, squares and diamonds denote the experimental data from Refs. [6,8]. The solid and dashed lines denote the results of the full calculation and the calculation including only the kaon final-state interactions (the strong and the Coulomb potential and the K-N rescattering), respectively. The theoretical results have been multiplied with a common normalization factor of 2.

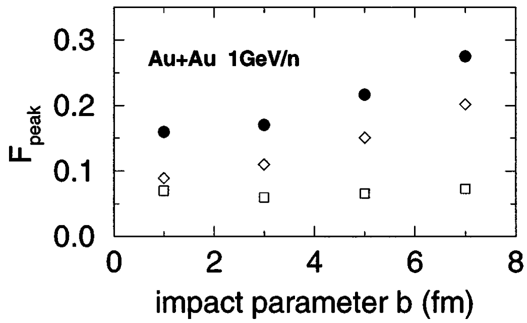

FIG. 5. The dependence of the kaon forward-backward enhancement defined in Eq. (2) on the impact parameter. The diamonds denote the contribution from the *K*-*N* rescattering, and the squares from the nonisotropic π-induced channel. The circles are the results of the full calculation including both effects.

K-*N* rescattering leads to a larger anisotropy of kaon emission for more peripheral collisions due to a larger number of spectator nucleons. Thus, if one wants to see the angular distribution of the kaons from the pion-induced channel, one should look to central collisions, since the reaction $\pi + B \rightarrow Y + K^+$ contributes there about 50% to the factor F_{peak}. For peripheral collisions it does less than 25%.

In conclusion, we have investigated the effects from the kaon final-state interactions as well as from the nonisotropic $\pi + B \rightarrow Y + K^+$ reaction on the kaon angular distribution in heavy ion reactions. The final-state interactions, which are mainly the *K*-*N* rescattering, the Coulomb and strong interaction potentials for kaons, have been shown to be insufficient to account for the observed forward-backward peak of the kaon angular distribution in the center-of-mass system for the reaction Au + Au at 1 GeV/nucleon. However, the π-induced reaction, including the *P*-wave contribution, has been found to substantially enhance the nonisotropic kaon emission, which reproduces the data. Thus we argue that the observed nonisotropic kaon emission may provide a support to this novel subthreshold kaon production mechanism $\pi + B \rightarrow Y + K^+$. To see the nonisotropic contribution of this channel, one should look to central collisions.

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