PHYSICAL REVIEW C VOLUME 42, NUMBER 5 NOVEMBER 1990

BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Contribution of $\pi N \rightarrow \Lambda K$ to subthreshold kaon production in heavy-ion collisions

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(Received 23 July 1990)

We have studied kaon production from the interaction of pions with nucleons in heavy-ion collisions at energies below the threshold for kaon production in the nucleon-nucleon interaction in free space. It is found that this contribution is less than 25% of the total kaon yield. The main contribution to kaon production is from baryon-baryon interactions and its magnitude depends sensitively on the nuclear equation of state at high densities.

The study of nuclear equation of state at high densities continues to be one of the main goals in intermediate-energy heavy-ion collisions. It has been proposed that the kaon yield from heavy-ion collisions at energies that are below the threshold for its production in the nucleon-nucleon interaction in free space is sensitive to the nuclear equation of state at high densities.[1] The argument goes as follows. Kaons are produced in interactions between nucleons through the process, $NN \rightarrow NYK$, where Y stands for either Λ or Σ hyperon. Since the initial energy of the nucleon is less than the energy required for kaon production, a kaon can only be produced after the nucleon has gained sufficient energy by undergoing multiple collisions with other nucleons. The nuclear density at which kaons are produced is thus high. The nuclear compression energy at high densities, which is not available to kaon production, is larger for a stiff equation of state than for a soft equation of state. As the kaon production probability decreases with nucleon energy, its yield from heavy-ion collisions will therefore be smaller for a stiff equation of state than for a soft equation of state. Due to the conservation of strangeness, kaons cannot be absorbed by nucleons and their relatively weak final-state interactions with nucleons will not change the dependence of the kaon yield on the nuclear equation of state. Indeed, it was demonstrated in Ref. 1 using the Vlasov-Uehling-Uhlenbeck (VUU) model[2] that for the collision of $Nb+Nb$ at 700 MeV/nucleon, the kaon production probability obtained with a soft equation of state, corresponding to the nuclear compressibility of 200 MeV, would be reduced by a factor of 3 if a stiff equation of state, corresponding to a compressibility of 380 MeV, was used. Similar conclusions were also obtained later in Ref. 3 using the analytical transport model.

But it was claimed in Ref. 4 that the inclusion of the momentum-dependent interaction between nucleons would affect kaon production more than the nuclear equation of state. Because of the deceleration of nucleons by the repulsive momentum-dependent interaction, the kaon yield was reduced by about a factor of 4 while a stiffer equation of state would lead to a reduction of only about 2. If this is indeed so, then it would be difficult to extract information on the nuclear equation of state from the measured kaon yield. The calculation of Ref. 4 is, however, inconsistent as the momentum-dependent interaction affects not only the dynamics of the collision but also modifies the kaon production cross section. As the nucleon effective mass is reduced by the momentum-dependent interaction, the kaon production cross section is expected to increase and the reduction of the kaon yield shown in Ref. 4 will be less appreciable.

Furthermore, medium effects on kaon production have been ignored in previous studies. Recently, we have investigated the modification of the kaon production cross section in nuclear matter.[5] In the one-pion exchange model,[6] the medium effect can be included by using the dressed pion propagator determined in the delta-hole model. The kaon production cross section in nuclear matter is found to increase with nuclear density. With the VUU model, we have obtained enhanced kaon production in heavy-ion collisions when the in-medium cross sections are used. Since the enhancement is only slightly larger for a soft equation of state than for a stiff equation of state, the total kaon yield remains therefore sensitive to the nuclear equation of state.

There are other processes which contribute also to kaon production. One process which may be important is the interaction between the produced pions and nucleons, i.e., $\pi N \rightarrow \Lambda K$. In Ref. 7 it was found that this process was essential in understanding kaon production in proton-nucleus reactions at energies below the threshold for its production in the nucleon-nucleon interaction in free space. But for heavy-ion collisions at 2.1 GeV, Cugnon and Lombard[8] showed in the cascade model that this process together with $\pi N \rightarrow \Sigma K$ contributed only about 25% to the total kaon yield. Its effect in heavy-ion collisions at subthreshold energies is not known and has not been included in Ref. 1. In this Brief Report, kaon production from the pion-nucleon interaction will be studied. We shall show that its effect is again small in heavy-ion collisions at subthreshold energies and that the conclusion of Ref. 1 remains valid.

To study kaon production from the pion-nucleon interaction, we need to include pions in the VUU model. At energies that we are interested in, pions are mainly produced from the decay of deltas which are created in the nucleon-nucleon inelastic scatterings. The mass of the produced delta is determined according to the probability distribution[9]

$$P(m_\Delta)=\frac{\frac{1}{4}\Gamma^2(q)}{(m_\Delta-m_0)^2+\frac{1}{4}\Gamma^2(q)} . \tag{1}$$

In the above, the centroid m_0 is 1232 MeV and the width $\Gamma(q)$ is given by

$$\Gamma(q)=\frac{0.47q^3}{[1+0.6(q/m_\pi)^2]m_\pi^2} , \tag{2}$$

where m_π is the pion mass and q is the momentum in the delta rest frame. According to Ref. 9 the use of a momentum-dependent width instead of the constant width of 115 MeV, which is used in Ref. 8, leads to a reduced pion yield in heavy-ion collisions and is considered to be an improved modeling of delta production.

The decay of the delta is treated statistically and is based on its half-life given by the inverse of its width. After its decay, a pion is produced isotropically in its rest frame. The motion of the pion then follows that of a free particle until it collides with another particle. The interaction of a pion with a nucleon is again through the delta resonance and is described by the cross section[8]

$$\sigma(E)=\frac{126}{1+4[(E-m_0)/0.115]^2} \text{ mb} , \tag{3}$$

where E is the pion-nucleon center-of-mass energy in GeV. This cross section is the pion-nucleon total cross section only when E is close to m_0. For large E, the pion-nucleon cross section is about 25 mb. In our calculation, we use thus 25 mb for the pion-nucleon total cross section once $\sigma(E)$ of Eq. (3) is less than this value. The interactions among pions are rare in heavy-ion collisions at intermediate energies and are therefore neglected.

We have used the VUU model to calculate the kaon yield from the collision of two Ca nuclei at an incident energy of 800 MeV/nucleon and at an impact parameter of $b=0.25$ fm, corresponding to the central collision. As in Refs. 1 and 5, kaon production is treated perturbatively by neglecting its effect on the dynamics of the collision. In this approach, a kaon is produced from the collision of two particles with the probability given by the ratio of the kaon production cross section to the total scattering cross section between the two particles. The kaon production cross section from baryon-baryon interaction is taken from the parametrization of Ref. 6 which has been used in Refs. 1 and 5. The cross section for $\pi N \rightarrow \Lambda K$ is taken from the parametrization of Ref. 8. Because the Σ mass is larger than the Λ mass, the process $\pi N \rightarrow \Sigma K$ is less important at subthreshold energies and has been neglected in our study.

The VUU model is solved with the test particle method by carrying out an ensemble of parallel cascade-type simulations. Because of the small number of energetic pions in each simulation, the probability for kaon production in pion-nucleon interactions is small. An efficient way to evaluate this probability is to allow pions and nucleons from different simulations to collide. The true kaon production probability is then obtained by dividing the total probability by the square of the number of simulations in the ensemble rather than simply the number of simulations as in the calculation of kaon production from nucleon-nucleon interactions.[1] This method is valid since we treat kaon production from pion-nucleon interactions perturbatively. A similar method has been used previously by us in studying dilepton production from pion-pion annihilations in the VUU model.[10]

We show in Fig. 1 the time evolution, obtained with the soft equation of state, of the central density, the number of delta and pion, and the number of baryon-baryon, nucleon-delta and pion-nucleon collisions. Since all deltas are produced in the initial high density stage, most nucleon-delta collisions, which accounts almost 80% of the kaons produced in baryon-baryon interactions, occur at this stage as well. On the other hand, only 60% of the total pion-nucleon collisions take place at this stage as pions are produced also in the expansion stage from the decay of deltas. In Fig. 2, the results for the stiff equation of state are shown. In this case, not only the central den-

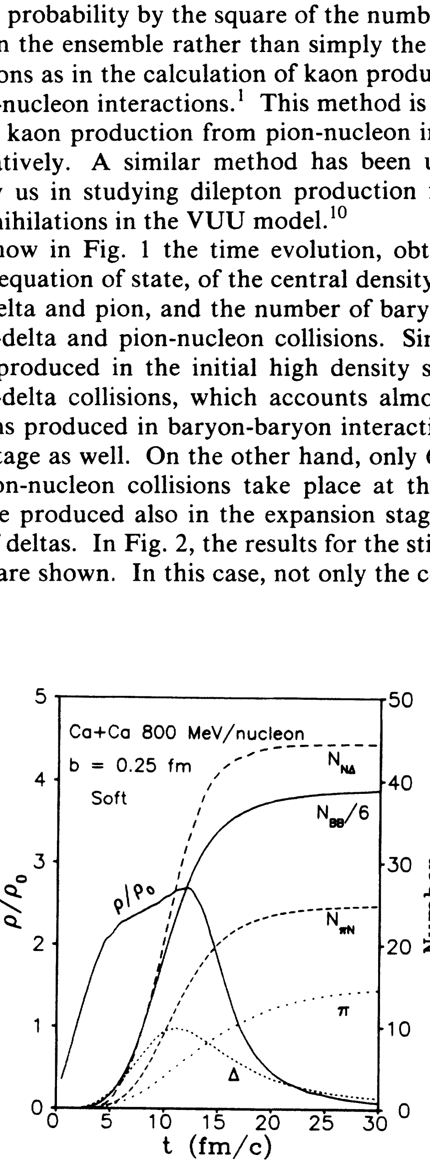

FIG. 1. Time evolution of the central density (ρ/ρ_0), the number of delta (Δ) and pion (π), and the number of baryon-baryon (N_{BB}), nucleon-delta ($N_{N\Delta}$), and pion-nucleon ($N_{\pi N}$) collisions for the collision of two Ca nuclei at 800 MeV/nucleon and at impact parameter $b=0.25$ fm with the soft equation of state. The value of N_{BB} has been divided by 6.

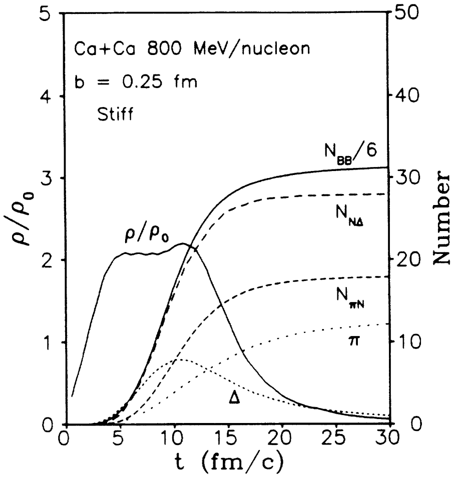

FIG. 2. Same as Fig. 1 but with the stiff equation of state.

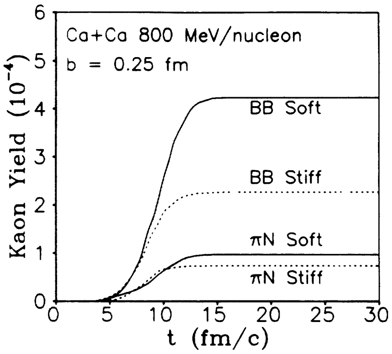

FIG. 3. The time evolution of the kaon yield.

sity is slightly lower but also the number of pion and delta and their collisions with nucleons are reduced.

In Fig. 3, the time evolution of the kaon yield is shown. The solid and dashed curves correspond to the results obtained with the soft equation of state and the stiff equation of state. For contributions only from baryon-baryon collisions, the kaon yield obtained with the soft equation of state is about a factor of 2 higher than that obtained with the stiff equation of state. This is similar to the results of Ref. 1. Since the number of pion-nucleon collisions does not change as much as the number of baryon-baryon collisions when different equations of state are used, the kaon yield from pion-nucleon collisions is less sensitive to the nuclear equation of state. They lead to an increase of the kaon yield by 20% for the soft equation of state and 30% for the stiff equations of state. The inclusion of kaon production from the pion-nucleon interaction reduces therefore only slightly the sensitivity of the kaon yield on the nuclear equation of state.

In conclusion, the kaon yield from the pion-nucleon interaction in heavy-ion collisions at intermediate energies has been calculated in the VUU model. We have found that this contribution is less than 25% of the total kaon yield, similar to that found in Ref. 8 for heavy-ion collisions at much higher energies. The suggestion of Ref. 1 that the kaon yield from heavy-ion collisions at subthreshold energies is sensitive to the nuclear equation of state at high densities remains valid. It is thus expected that experiments currently carried out at GSI (Ref. 11) on subthreshold kaon production in heavy-ion collisions will provide us with useful information on the nuclear equation of state at high densities.

This work was supported in part by the National Science Foundation under Grant No. PHY-8907986 and the Robert A. Welch Foundation under Grant No. A-1110.

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