Contribution of the reaction $NY \rightarrow NN\bar{K}$ to antikaon production in relativistic heavy-ion collisions

Che Ming Ko
Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843
(Received 3 November 1983)

The isospin-averaged cross section for the reaction $NY \rightarrow NN\bar{K}$ is calculated in the one-pion exchange model. This reaction is relevant to the production of antikaons in heavy-ion collisions at subthreshold energies. Using a simplified kinetic model in which antikaons are produced from the interaction of hyperons with the thermalized participant hadrons, it is estimated that the contribution to antikaon productions from the reaction $NY \rightarrow NN\bar{K}$ is only a few percent of that from the reaction $\pi Y \rightarrow N\bar{K}$.

Heavy-ion collisions offer the possibility of studying the properties of nuclear matter under unusual conditions. In low energy collisions of <20 MeV/nucleon, one can study fast spinning nuclei, as angular momentum up to many tens $\hbar$ can be brought into the nuclei.[1] At intermediate energies of 20—200 MeV/nucleon, the temperature of nuclear matter can be raised to more than ~ 10 MeV and it is possible to study the interesting gas-liquid phase transition of the nuclear matter.[2] For even higher energies of 200—2000 MeV/nucleon, particle productions become increasingly important and one thus reaches the region of the transition to hadronic matter. Possible new phases of matter, such as the pion condensate[3] and the Lee-Wick abnormal state,[4] may be created when the density of the matter is large. At ultrarelativistic energies of >20 GeV/nucleon in colliding beams, the energy density during the collision can reach >2 GeV/fm^3, which may lead to the appearance of the quark-gluon plasma.[5]

Regarding particle productions in heavy-ion collisions, pions have been most extensively studied.[6] Only very recently have the strange particle productions been investigated.[7–9] The most interesting data were from the experiments carried out at Bevalac to detect K^- in heavy-ion collisions at an incident energy of 2.1 GeV/nucleon.[9] The threshold for K^- production in the nucleon-nucleon collision is ~ 2.5 GeV. The observation of K^- at subthreshold energies in heavy-ion collisions implies that more than one projectile nucleon must be involved in converting their kinetic energies into the mass of K^-. This experiment provides, therefore, the possibility of studying nuclear collective effects, such as Fermi motions, coherent productions, and multiple collisions. Shor *et al.*[9] showed that the simple nucleon-nucleon collision model with Fermi motions underestimates the number of K^- by more than an order of magnitude. Muller[10] suggested that the decay of the coherently produced ϕ meson into K^+K^- might be responsible for the enhanced production of K^-. But his predicted K^- energy spectrum disagrees with that of the experiment. On the other hand, it was shown recently that the observed K^- production cross section can be largely explained by the strangeness-exchange reactions $\pi Y \rightarrow \bar{K}N$ between the hyperons and pions initially produced in the collision.[11] If the final state interactions of K^- with the hadronic matter are taken into account, the observed K^- energy spectrum can also be understood qualitatively.[12]

There is another process $NY \rightarrow NN\bar{K}$ which may also contribute to the production of antikaons in heavy-ion collisions. Since the threshold energies for this process are ~ 455 MeV and ~ 635 MeV for $Y=\Sigma$ and $Y=\Lambda$, respectively, and are larger than those for the process $\pi Y \rightarrow \bar{K}N$, which are ~ 120 MeV and ~ 215 MeV for $Y=\Sigma$ and $Y=\Lambda$, respectively, one might intuitively think that the contribution from the reaction $NY \rightarrow NN\bar{K}$ is negligible. To ensure that this is indeed so requires the knowledge of the cross section for the process $NY \rightarrow NN\bar{K}$. Unfortunately, this information is not available empirically.

In this paper, the one-pion exchange model will be used to calculate the isospin-averaged cross section for the reaction $NY \rightarrow NN\bar{K}$. In high-energy heavy-ion collisions, hyperons are produced mostly at rest in the fireball via the reaction $NN \rightarrow NYK$. Assuming that the participant nucleons form a thermalized fireball, the fraction of hyperons which are converted into nucleons via the reaction $NY \rightarrow NN\bar{K}$ will be estimated in a simplified kinetic model. The results will then be compared with that from Ref. 11 in which the hyperons interact with the pions in the fireball via the process $\pi Y \rightarrow N\bar{K}$.

The one-pion exchange model was extensively used in the study of the associated production of strange particles in nucleon-nucleon collisions.[13] The Feynman diagram for the reaction $NY \rightarrow NN\bar{K}$ in the one-pion exchange model is shown in Fig. 1. Using the standard Feynman rules, the isospin-averaged total cross section for this reac-

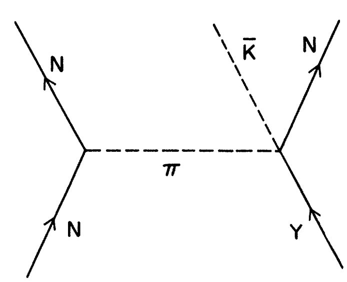

FIG. 1. Feynman diagram for the process $NY \rightarrow NN\bar{K}$ in the one-pion exchange model.

tion can be written as

$$\bar{\sigma}=\frac{M_N^2}{8\pi^2(pU)^2}\int_{W_{\min}}^{W_{\max}} dW\,2kW^2 \times\int_{\Delta_-^2}^{\Delta_+^2} d\Delta^2\frac{f^2(\Delta^2)}{\mu^2}\frac{\Delta^2}{(\Delta^2+\mu^2)^2} \times\bar{\sigma}_0(W;\Delta^2)\ . \tag{1}$$

In the above, M_N and μ are, respectively, the nucleon mass and the pion mass. The magnitude of the three-momentum of the initial particles in the c.m. system is p while the total energy in the c.m. system is U. With the total energy in the c.m. system of the pion and the hyperon being denoted by W, the momentum k of either the pion or the hyperon is given by

$$k=\frac{1}{2W}[W^4-2W^2(\mu^2+M_Y^2)+(\mu^2-M_Y^2)^2]^{1/2}\ , \tag{2}$$

where M_Y is the mass of the hyperon. The four-momentum of the virtual pion is Δ. The quantity $f(\Delta^2)$ is the πNN form factor with normalization such that $f(\Delta^2=-\mu^2)\simeq 1.0$ and is usually taken to be of the monopole form, i.e.,

$$f(\Delta^2)=f(\mu^2)\frac{\Lambda^2-\mu^2}{\Lambda^2+\Delta^2}\ , \tag{3}$$

with $\Lambda\simeq 1$ GeV. The limits of integration are given by

$$W_{\min}=M_K+M_N,\quad W_{\max}=U-M_N\ , \tag{4}$$

and

$$\Delta_\pm^2=2EE'-2M_N^2\pm 2pp'\ , \tag{5}$$

where $E=(p^2+M_N)^{1/2}$ is the energy of the initial nucleon in the c.m. system while p' and E' are the momentum and energy of the same nucleon in the final state, i.e.,

$$p'=[U^2-(W+M_N)^2]^{1/2}[U^2-(W-M_N)^2]^{1/2}/2U\ , \tag{6}$$

and $E'=(p'^2+M_N^2)^{1/2}$. The quantity $\bar{\sigma}_0(W;\Delta^2)$ is the isospin-averaged cross section for the virtual process $\pi Y\rightarrow N\bar{K}$ and is unknown. As an example, for a nucleon with kinetic energy 1 GeV incident on a lambda, one obtains $0.26\ \mathrm{GeV}^2<\Delta^2<1.286\ \mathrm{GeV}^2$. Since $-\mu^2\simeq -0.02\ \mathrm{GeV}^2$, the pion in this model is thus off shell. Because of the pole structure of the Δ^2 integration in Eq. (1), the dominant contribution to the cross section $\bar{\sigma}$ comes from $\bar{\sigma}_0(W;\Delta^2)$ near the mass shell. In the energy range considered, $\bar{\sigma}_0(W;\Delta^2)$ is expected to have a smooth dependence on Δ^2; therefore the on-shell approximation

$$\bar{\sigma}_0(W;\Delta^2)\approx\bar{\sigma}_0(W;-\mu^2)\equiv\sigma_0(W)$$

is probably a good one. Since the one-pion exchange model with on-shell approximation to the virtual process $\pi N\rightarrow YK$ has been successful in describing the strange particle production $NN\rightarrow NYK$, the same approximation is used here for the process $NY\rightarrow NN\bar{K}$.

The on-shell cross section for the reaction $\pi Y\rightarrow N\bar{K}$ has been measured experimentally. According to the analysis of Martin and Ross,[14] the experimental data on K^-p and K^0p reactions below 280 MeV/c can be parametrized in terms of nine real S-wave K-matrix elements in the space of the three channels $\bar{K}N$, $\Sigma\pi$, and $\Lambda\pi$. Among them, three are for isospin $I=0$ and six are for $I=1$, i.e.,

$$K_0=\begin{bmatrix}\alpha_K & \alpha_{K\Sigma}\\ \alpha_{K\Sigma} & \alpha_\Sigma\end{bmatrix},\quad K_1=\begin{bmatrix}\beta_K & \beta_{K\Sigma} & \beta_{K\Lambda}\\ \beta_{K\Sigma} & \beta_\Sigma & \beta_{\Sigma\Lambda}\\ \beta_{K\Lambda} & \beta_{\Sigma\Lambda} & \beta_\Lambda\end{bmatrix}\ . \tag{7}$$

In units of fm, they have the following values:

$$\alpha_K=-2.40,\quad \alpha_{K\Sigma}=-1.21,\quad \alpha_\Sigma=-1.05\ ,$$
$$\beta_K=-0.01,\quad \beta_{K\Sigma}=-0.71,\quad \beta_{K\Lambda}=-0.38\ ,$$
$$\beta_\Sigma=0.34,\quad \beta_{\Sigma\Lambda}=-0.21,\quad \beta_\Lambda=0.17\ .$$

The T matrix is related to the K matrix via the relation

$$T^{-1}=K^{-1}-iQ\ , \tag{8}$$

where Q is a diagonal matrix of the channel c.m. momenta, i.e.,

$$Q=\begin{bmatrix}q_K & 0 & 0\\ 0 & q_\Sigma & 0\\ 0 & 0 & q_\Lambda\end{bmatrix}\ , \tag{9}$$

corresponding to $\bar{K}N$, $\Sigma\pi$, and $\Lambda\pi$ channels, respectively.

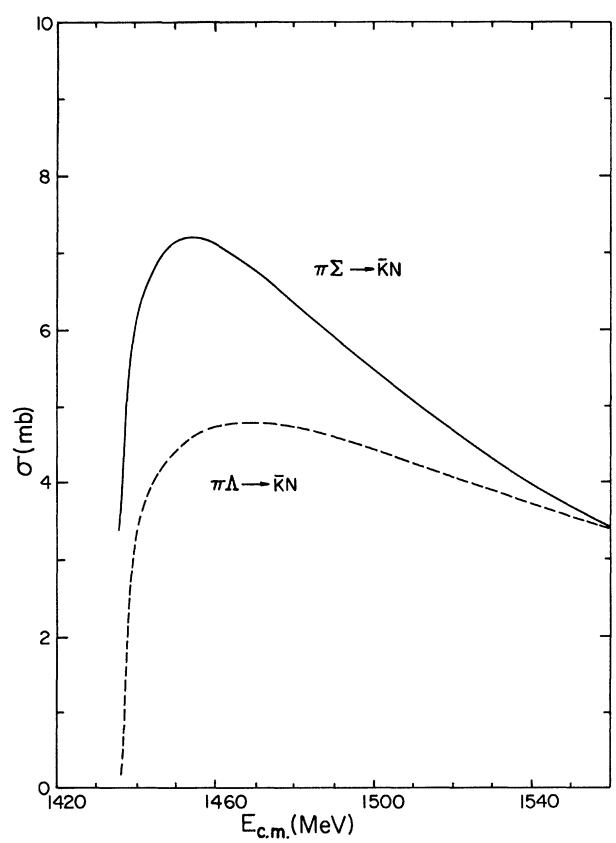

FIG. 2. Isospin-averaged cross sections for the strangeness-exchange reactions as functions of the total center-of-mass energy.

The isospin-averaged cross section from an initial channel i to a final channel f is then given by

$$\bar{\sigma}(i\to f)=\frac{4\pi(q_f/q_i)}{(2I_1+1)(2I_2+1)}\sum_I (2I+1)\,|\,T_I(i\to f)\,|^2 , \tag{10}$$

where I_1 and I_2 are the isospins of the two particles in the initial channel. The calculated isospin-averaged cross sections are shown in Fig. 2 as functions of the total c.m. energy.

Using the above cross sections, one can then numerically evaluate Eq. (1) to obtain the isospin-averaged cross sections for the reaction $NY\to NN\bar{K}$. The results of the calculations show that these cross sections can be approximately parametrized by

$$\bar{\sigma}(NY\to NN\bar{K})\cong A(E_{\rm kin}-E_{\rm kin}^{\rm thr})\mu_b , \tag{11}$$

with $A\simeq 0.8$ and 1.2 for $Y=\Lambda$ and Σ, respectively. In the above, $E_{\rm kin}^{\rm thr}$ is the threshold kinetic energy and $E_{\rm kin}$ is the kinetic energy of the nucleon in the rest frame of the hyperon, both being in units of MeV. For nucleons with kinetic energy less than 1.5 GeV, the magnitudes of these cross sections are <1 mb and are therefore quite small in comparison with that of the strangeness-exchange reactions $\pi Y\to N\bar{K}$, which are ~ 5 mb.

In Refs. 11 and 12, antikaon productions at subthreshold energies in high-energy heavy-ion collisions were studied in a simplified kinetic model and it was found that the reaction $\pi Y\to K\bar{N}$ between the pions and the hyperons initially produced in the fireball contributed significantly to the production of antikaons. The generalization of the kinetic model to include the contribution to antikaon productions from the process $NY\to NN\bar{K}$ is straightforward. The parameter which determines the fraction of hyperons which are converted into antikaons after interacting with nucleons is given by the reaction rate for the process $NY\to NN\bar{K}$. Assuming that the hyperon is initially produced at rest in the fireball frame, then this reaction rate is the average of the product $\sigma(NY\to NN\bar{K})v_N\rho_N$ over the normalized nucleon momentum distribution $f(\vec{p})$, i.e.,

$$\tau_{NY\to NN\bar{K}}^{-1}=\int d^3\vec{p}\,\bar{\sigma}(NY\to NN\bar{K})v_N\rho_N f(\vec{p})d^3\vec{p} . \tag{12}$$

In the above, ρ_N and v_N are, respectively, the nucleon density and the velocity of the nucleon in the fireball. Following Ref. 11, the nucleon distribution function is taken as a Maxwellian form characterized by the temperature T, then

$$\tau_{NY\to NN\bar{K}}^{-1}=\frac{4\rho_N}{(2M_N\pi)^{1/2}}\frac{1}{T^{3/2}}\times\int_{E_{\rm kin}^{\rm thr}}^{\infty} dE_{\rm kin}E_{\rm kin}e^{-E_{\rm kin}/T}\bar{\sigma}(NY\to NN\bar{K}) , \tag{13}$$

where $E_{\rm kin}$ is the kinetic energy of the nucleon in the fireball frame. Using the calculated cross section for $NY\to NN\bar{K}$ as parametrized by Eq. (11), one has

$$\tau_{NY\to NN\bar{K}}^{-1}=\frac{4\rho_N T^{3/2}A}{(2M_N\pi)^{1/2}}\left[2+\frac{E_{\rm kin}^{\rm thr}}{T}\right]e^{-E_{\rm kin}^{\rm thr}/T} . \tag{14}$$

As in Ref. 11, the temperature T is taken to be ≈ 130 MeV while the nucleon density ρ_N is $\approx 2\rho_0=0.34$ fm^{-3}; then one obtains

$$\tau_{N\Lambda\to NN\bar{K}}^{1}\simeq 3.3\times 10^{19}\ {\rm s}^{-1} ,\qquad \tau_{N\Sigma\to NN\bar{K}}^{-1}\simeq 1.6\times 10^{20}\ {\rm s}^{-1} , \tag{15}$$

which are much smaller than the reaction rates due to the process $\pi Y\to N\bar{K}$ which were computed in Ref. 11 and have the following values:

$$\tau_{\pi\Lambda\to N\bar{K}}^{-1}\simeq 1.7\times 10^{21}\ {\rm s}^{-1} .\qquad \tau_{\pi\Sigma\to N\bar{K}}^{-1}\simeq 2.4\times 10^{21}\ {\rm s}^{-1} . \tag{16}$$

In the simplified kinetic model of Ref. 11, the number of antikaons $N_{\bar{K}}$ is related to the initial number of hyperons $N_Y^{(0)}$ by

$$N_{\bar{K}}=N_Y^{(0)}/(1+\tau_{Y\bar{K}}/\tau_{\bar{K}Y}) , \tag{17}$$

if one assumes that the $N_{\bar{K}}$ approaches its equilibrium value during the collision. In the above,

$$\tau_{Y\bar{K}}^{-1}\approx\tau_{\pi Y\to N\bar{K}}^{-1}+\tau_{NY\to NN\bar{K}}^{-1} ,\qquad \tau_{\bar{K}\Lambda}^{-1}\approx\tau_{N\bar{K}\to\pi\Lambda}^{-1}\approx 5.4\times 10^{22}\ {\rm s}^{-1} ,\qquad \tau_{\bar{K}\Sigma}^{-1}\approx\tau_{N\bar{K}\to\pi\Sigma}^{-1}\approx 1.3\times 10^{23}\ {\rm s}^{-1} , \tag{18}$$

one has thus neglected the absorption of $\bar{K}$ by two nucleons in comparison with the strangeness exchange reaction $N\bar{K}\to\pi Y$. Using values in Eqs. (15) and (16), it is seen that the contributions to antikaon productions from the processes $N\Lambda\to NN\bar{K}$ and $N\Sigma\to NN\bar{K}$ are only $\sim 2\%$ and $\sim 7\%$ of those from the processes $\pi\Lambda\to N\bar{K}$ and $\pi\Sigma\to N\bar{K}$, respectively. This conclusion still holds if one uses different values for the model parameters such as density (ρ_N,ρ_π) and temperature T of the fireball. For example, if the nucleon density is reduced by a factor of 2, the reaction rate $\tau_{NY\to NN\bar{K}}^{-1}$ decreases approximately by the same factor. Although the fireball model then predicts a slight increase of the pion density, the reaction rate $\tau_{\pi Y\to N\bar{K}}^{-1}$ is reduced instead by $\sim 20\%$ due to the decrease of the fireball temperature. The relative importance of the two contributions changes thus by less than a factor of 2 when the density is reduced by half. On the other hand, the reaction rate $\tau_{N\bar{K}\to\pi Y}^{-1}$ decreases also by $\sim$ a factor of 2; the number of hyperons being converted into $\bar{K}$ is, therefore, about the same in both densities.

In summary, the isospin-averaged cross section for the reaction $NY\to NN\bar{K}$ has been calculated in the one-pion exchange model. The magnitude of the cross section is found to be negligibly small for nucleons with kinetic energy <1.5 GeV. Using a simplified kinetic model as proposed in Ref. 11, which assumes that the hadrons in the participant region form a thermally equilibrated fireball, the contribution of the process $NY\to NN\bar{K}$ to the production of an antikaon in high-energy heavy-ion collisions is only a few percent of that from the process $\pi Y \rightarrow N\bar{K}$. To substantiate the above conclusions, it is of course necessary to carry out the following studies in the future: (1) the on-shell approximation to the virtual process $\pi Y \rightarrow N\bar{K}$ in the one-pion exchange model needs to be checked; and (2) a more realistic dynamic model for describing the multistep processes in heavy-ion collisions should be studied. In particular, to compare with experimental data it is essential to also take into account the contributions from nonthermal nucleons via the same process $NY \rightarrow NN\bar{K}$. This may be done in the framework of the nuclear cascade model.

This work was supported in part by a National Science Foundation grant under contract no. PHY81-09019.

[1]R. M. Diamond and F. S. Stephens, Annu. Rev. Nucl. Part. Sci. 30, 85 (1980).
[2]G. F. Bertsch and P. J. Siemens, Phys. Lett. 126B, 9 (1983).
[3]A. B. Migdal, Rev. Mod. Phys. 50, 107 (1978).
[4]T. D. Lee, Rev. Mod. Phys. 47, 267 (1975).
[5]M. Gyulassy, Nucl. Phys. A400, 31C (1983).
[6]S. Nagamiya *et al.*, Phys. Rev. C 24, 971 (1981).
[7]S. Schnetzer *et al.*, Phys. Rev. Lett. 49, 989 (1982).
[8]J. W. Harris *et al.*, Phys. Rev. Lett. 47, 229 (1981).
[9]A. Shor *et al.*, Phys. Rev. Lett. 48, 1597 (1982); contributed papers in Proceedings of the Sixth High-Energy Heavy-Ion Study, Berkeley, 1983, p. 109.
[10]K. H. Muller, Nucl. Phys. A395, 509 (1983).
[11]C. M. Ko, Phys. Lett. 120B, 294 (1983).
[12]C. M. Ko, Phys. Lett. (in press).
[13]T. Yao, Phys. Rev. 125, 1048 (1961), and references therein.
[14]A. D. Martin and G. G. Ross, Nucl. Phys. B16, 479 (1970).