Preferential emission of pions in asymmetric nucleus-nucleus collisions

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Pion production in Ne on Pb collisions at a beam energy of 800 MeV/nucleon is studied by solving a coupled set of transport equations for the phase-space distribution functions of nucleons, deltas, and pions. The experimentally observed preferential emission of pions away from the interaction zone towards the projectile side in the transverse direction is found to be due to the stronger pion absorption by the heavier target spectator. A model calculation of the pion transverse momentum distribution in the reaction plane agrees with that of the experimental data.

The existence of a collective flow signature among the final-state baryons of relativistic heavy-ion collisions at beam energies around 1 GeV/nucleon has been firmly established by the in-plane transverse momentum analysis [1]. Due to the small mass of pions compared to that of baryons, it has been pointed out that the pions might serve as a good probe of any hydrodynamical flow [2]. Moreover, as pions are mainly coming from the decay of Δ resonances in the relativistic heavy-ion collisions, the remnant of the collective flow carried by Δ resonances might be seen in the final-state pions.

Looking for flow signatures among pions, several groups [2–4] have studied the transverse momentum distribution in the reaction plane for pions (average transverse momentum in the reaction plane $\langle p_x \rangle$ versus rapidity y). One of the most striking results from the DIOGENE Collaboration [2] is that the in-plane transverse momentum of pions is always positive even for backward rapidities, for the asymmetric (Ne or Ar)+(Nb or Pb) systems.

However, the intranuclear-cascade model predicts values compatible with zero over the whole range of rapidity [2]. The quantum-molecular-dynamics model calculation of the pion transverse momentum distribution [5] indicates that the introduction of the mean field describes some of the experimental effect, but the model predicts less asymmetry than observed experimentally. Therefore, the question whether the experimentally observed preferential emission of pions away from the interaction zone towards the projectile side in the asymmetric nucleus-nucleus collisions is due to the collective flow of pions or due to the shadowing effect of the heavier target spectator has not been resolved.

In this article we report on the results of a study using a hadronic transport model [6–8]. The preferential emission of pions toward the projectile side in the transverse direction in the reaction Ne+Pb at a beam energy of 800 MeV/nucleon is found to be due to the stronger absorption of pions by the heavier target spectator. The calculated transverse momentum distribution of pions in the reaction plane agrees with that of the experimental data.

The calculations were performed by numerically solving a coupled set of transport equations for the phase-space distribution functions of nucleons, deltas, and pions. The transport equation for the particular state b of the baryon (nucleon and delta) reads [7,8]

$$\frac{\partial f_b(xp)}{\partial t}+\frac{\mathbf{p}}{E_b}\cdot\nabla_r f_b(xp)-\nabla_r U(x)\cdot\nabla_p f_b(xp)=I^b_{bb}(xp)+I^b_{b\pi}(xp)\ , \qquad (1)$$

where we have used the notation $x=(t,\mathbf{r})$. The collision terms $I^b_{bb}(xp)$ and $I^b_{b\pi}(xp)$ on the right-hand side of the equation are the rate of change of the baryon phase-space distribution function due to baryon-baryon collisions and baryon-pion collisions.

For any charge state of the pion we have

$$\frac{\partial f_\pi(xk)}{\partial t}+\frac{\mathbf{k}}{E_\pi}\cdot\nabla_r f_\pi(xk)=I^\pi_{b\pi}(xk)\ , \qquad (2)$$

where $I^\pi_{b\pi}(xk)$ is the rate of change of the pion phase-space distribution function due to baryon-pion collisions. In the above equations we have used $p=(E,\mathbf{p})$ for the four-momentum of baryons and $k=(E_\pi,\mathbf{k})$ for that of pions.

The baryon-baryon collision term can be written as

$$\begin{aligned}I^b_{bb}(xp)=\pi\sum_{\alpha_1\alpha_2\alpha_3,m^b_s}\int\int\int&\frac{M_bM_{\alpha_1}M_{\alpha_2}M_{\alpha_3}}{E_bE_{\alpha_1}E_{\alpha_2}E_{\alpha_3}}W^b_{bb}(p_1\alpha_1,p_2\alpha_2,p_3\alpha_3,p\alpha_b)\\&\times[f_{\alpha_2}(xp_2)f_{\alpha_3}(xp_3)\bar{f}_{\alpha_1}(xp_1)\bar{f}_b(xp)-\bar{f}_{\alpha_2}(xp_2)\bar{f}_{\alpha_3}(xp_3)f_{\alpha_1}(xp_1)f_b(xp)]\\&\times\delta^{(4)}(p+p_1-p_2-p_3)\frac{1}{(2\pi)^9}d\mathbf{p}_1d\mathbf{p}_2d\mathbf{p}_3\ .\end{aligned} \qquad (3)$$

Here, the label $\alpha=(b,m_s,m_t)$, where $b=N$ or Δ and m_s/m_t is the spin/isospin of the baryon. $W^b_{bb}(p_1\alpha_1,p_2\alpha_2,p_3\alpha_3,p\alpha_b)$ is the square of the transition matrix element in baryon-baryon collisions, which determines the transition rate. It has been simulated by using the free-space elementary cross sections [8]. The above baryon-baryon collision term respects the Pauli exclusion principle as shown in the appearance of the Fermi-Dirac factors

$$\bar{f}_\alpha(xp)=1-f_\alpha(xp) \tag{4}$$

and

$$\bar{f}_b(xp)=1-f_b(xp)\ . \tag{5}$$

It is of the same structure as the NN collision term appearing in the standard BUU equation, but generalized to accommodate the four Δ states of the baryon.

The collision terms due to baryon-pion interactions can be written as

$$\begin{aligned} I^b_{b\pi}(xp)=\frac{\pi}{8}\sum_{\pi\alpha' m_s^b}\int\int\frac{M_bM_{\alpha'}}{E_b(p)E_{\alpha'}(p')}W^b_{b\pi}(\alpha'p',\pi k,\alpha p)\\ \times\{[\bar{f}_\pi(xk)f_{\alpha'}(xp')\bar{f}_b(xp)-f_\pi(xk)\bar{f}_{\alpha'}(xp')f_b(xp)]\delta^{(4)}(p'-k-p)\\ +[f_\pi(xk)f_{\alpha'}(xp')\bar{f}_b(xp)-\bar{f}_\pi(xk)\bar{f}_{\alpha'}(xp')f_b(xp)]\delta^{(4)}(p'+k-p)\}\frac{1}{(2\pi)^6}d\mathbf{p}'d\mathbf{k} \end{aligned} \tag{6}$$

and

$$\begin{aligned} I^\pi_{b\pi}(xk)=\frac{\pi}{16}\sum_{\alpha\alpha'}\int\int\frac{M_\alpha M_{\alpha'}}{E_\alpha(p)E_{\alpha'}(p')}W^\pi_{b\pi}(\alpha p,\alpha'p',\pi k)[\bar{f}_\pi(xk)f_{\alpha'}(xp')\bar{f}_\alpha(xp)-f_\pi(xk)f_\alpha(xp)\bar{f}_{\alpha'}(xp')]\\ \times\delta^{(4)}(p'-p-k)\frac{1}{(2\pi)^6}d\mathbf{p}\,d\mathbf{p}'\ . \end{aligned} \tag{7}$$

In Eqs. (6) and (7) the index π has been used to specify the isospin quantum number of the pion, and the Bose-Einstein factors are

$$\bar{f}_\pi(xk)=1+f_\pi(xk)\ . \tag{8}$$

$W^b_{b\pi}(\alpha'p',\pi k,\alpha p)$ and $W^\pi_{b\pi}(\alpha p,\alpha'p',\pi k)$ are the square of the transition matrix element for the corresponding processes, again their effects have been simulated by using the free space resonance cross sections and the width of the resonances.

The above equations are the general expressions for the collision integrals, and the matrix elements in these equations assure that only physical processes can happen. For example, only when b specifies a nucleon do the first terms in the above two equations contribute, while only when b specifies a Δ the second terms contribute. It is worth noting that the fermion suppression factors and the boson enhancement factors are included in these collision terms and follow from the derivation [7].

The solution to the above coupled transport equations were obtained by using the test particle method [9] as in solving the standard BUU transport equation [10,11], and the detailed description of the numerical realization procedures has been given in previous publications [6,8].

We now turn to the calculation of the pion transverse momentum distribution in the reaction plane. In the model calculation, the reaction plane is known *a priori* and we refer this plane as the true reaction plane in the following discussions. The reaction plane estimated from the observed charged particles will be referred to as the estimated reaction plane. To study the mechanism for the preferential emission of pions in the transverse direction, we first study the pion transverse momentum distribution in the true reaction plane without using the experimental detector filter.

In Fig. 1 the rapidity distribution and the transverse momentum distribution (scaled with the mass of the pion)

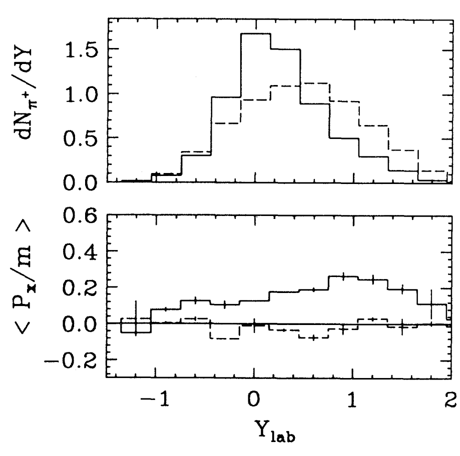

FIG. 1. Upper figure: π^+ rapidity distribution calculated with (solid histogram) and without (dashed histogram) the pion reabsorption channels for the reaction of Ne+Pb at $E/A=800$ MeV and the impact parameter of 3 fm. For ease of comparison, the overall normalization of both curves was fixed to the same value. Lower figure: calculated π^+ transverse momentum distributions in the true reaction plane with (solid histogram) and without (dashed histogram) the pion reabsorption channels.

in the true reaction plane for π^+ from the reaction Ne+Pb at a beam energy of 800 MeV/nucleon are shown with the solid histograms. The calculation was done at an impact parameter of 3 fm which coincides with the condition of the experimental data [2]. It is seen that the rapidity distribution peaks near the center-of-mass rapidity of 0.1 unit and the transverse momentum of pions in the true reaction plane is positive even for negative rapidities, which reflects the fact that the pions are preferentially emitted toward one side of the participant region.

In the baryon transverse momentum analysis, the S-shaped distribution in the reaction plane with the average in-plane transverse momentum $\langle p_x \rangle$ positive (negative) for positive (negative) rapidities in the c.m. system for repulsive interactions has been taken as a signature of the collective baryon flow [1], and S-shaped distributions of opposite sign are also found in the beam energy region below 100 MeV/nucleon where attractive interactions dominate [12]. Both the flow parameter and the average in-plane transverse momentum have been found to be sensitive to the nuclear equation of state [13,14].

Is the nonzero in-plane transverse momentum of pions a remnant of the baryon collective flow carried by Δ resonances? To answer this question we have studied the dependence of the pion transverse momentum distribution on the nuclear equation of state. Within statistical fluctuations, results from the calculations done with a stiff equation of state corresponding to the nuclear compressibility of $K=380$ and with a soft equation of state corresponding to $K=210$ are the same. This indicates that the effect of baryon collective flow on the pion transverse momentum distribution is negligible and the origin of the positive in-plane transverse momentum of pions is not predominantly the remnant of the Δ flow.

It has been speculated that the mechanism that causes the positive pion transverse momentum in the reaction plane might be due to the target shadowing effect [3,2], and this idea has been demonstrated in a phenomenological model assuming that pions have a constant mean free path in nuclear matter [15].

In the present dynamical model calculation pions are reabsorbed through a two-step mechanism, namely,

$$\pi+N\rightarrow\Delta, \quad N+\Delta\rightarrow N+N \ . \tag{9}$$

The cross section for the pion-nucleon resonance is parametrized using the fixed width Breit-Wigner formula with the maximum cross section from the experimental data [16],

$$\sigma_{\max}(\pi^+p\rightarrow\Delta^{++})=\sigma_{\max}(\pi^-n\rightarrow\Delta^-)=200\text{ mb} , \tag{10}$$

$$\sigma_{\max}(\pi^0p\rightarrow\Delta^{+})=\sigma_{\max}(\pi^0n\rightarrow\Delta^0)=135\text{ mb} , \tag{11}$$

$$\sigma_{\max}(\pi^-p\rightarrow\Delta^{0})=\sigma_{\max}(\pi^+n\rightarrow\Delta^+)=70\text{ mb} , \tag{12}$$

$$\sigma_{\max}(\pi^-p\rightarrow N^{*0})=\sigma_{\max}(\pi^0n\rightarrow N^{*0})=50\text{ mb} , \tag{13}$$

$$\sigma_{\max}(\pi^+n\rightarrow N^{*+})=\sigma_{\max}(\pi^0p\rightarrow N^{*+})=50\text{ mb} . \tag{14}$$

The cross section for the Δ reabsorption process in each isospin channel is determined from detailed balance,

$$\sigma(\Delta^+p\rightarrow pp)=\frac{1}{4}\frac{p_f^2}{p_i^2}\sigma(pp\rightarrow\Delta^+p) , \tag{15}$$

$$\sigma(\Delta^{++}n\rightarrow pp)=\frac{1}{4}\frac{p_f^2}{p_i^2}\sigma(pp\rightarrow\Delta^{++}n) , \tag{16}$$

$$\sigma(\Delta^+n\rightarrow pn)=\frac{1}{2}\frac{p_f^2}{p_i^2}\sigma(pn\rightarrow\Delta^+n) , \tag{17}$$

$$\sigma(\Delta^0p\rightarrow pn)=\frac{1}{2}\frac{p_f^2}{p_i^2}\sigma(pn\rightarrow\Delta^0p) . \tag{18}$$

By using isospin symmetry and averaging over the isospin degree of freedom the above relations reduce to

$$\sigma(N\Delta\rightarrow NN)=\frac{1}{8}\frac{p_f^2}{p_i^2}\sigma(NN\rightarrow N\Delta) . \tag{19}$$

Here p_f is the momentum in the final NN channel in the c.m. of the colliding particles and the Δ production cross sections are parametrized by using the experimental data as in Ref. [17]. This assumes that the resonance is narrow; in general Eq. (19) underestimates the absorption rate of low energy Δ's [18].

To study the effect of the pion reabsorption and rescattering and therefore check the shadowing effect in forming the positive in-plane transverse momentum of pions, we calculated the pion transverse momentum distribution and the rapidity distribution by turning off the pion reabsorption channels (9) and the Δ rescattering channel $N+\Delta\rightarrow N+\Delta$. Results of this calculation are shown with the dashed histograms in Fig. 1. (For ease of comparison we have normalized the total production cross section of these primordial pions to the one for the pions produced including the reabsorption and rescattering channels.) In this case the in-plane transverse momentum is zero within statistical error bars and the rapidity distribution is symmetric about half-beam rapidity of 0.6 unit, which reflects the fact that the pions are emitted isotropically in the center-of-mass frame of two colliding nucleons.

Comparing the rapidity distributions obtained with and without the reabsorption and rescattering channels (solid histogram and dashed histogram), we first notice that pions with positive rapidities emitted toward the target side are more reabsorbed compared to the pions with negative rapidities emitted toward the projectile side, as one would expect for the highly mass-asymmetric system. Second, the reabsorption and reemission of pions as well as the rescattering of Δ's help to thermalize the system. This effect appears as the change of the peak of the rapidity distribution from the midrapidity to the center-of-mass rapidity as the reabsorption, reemission, and the rescattering channels are turned on.

From the results of these calculations, it is clear that the positive in-plane transverse momentum of pions in the asymmetric nucleus-nucleus collisions is due to the stronger reabsorption of pions by the heavier target and therefore the speculation about the shadowing effect of the target is confirmed.

In symmetric nucleus-nucleus collisions the spectators are the same on both sides of the interaction zone. It is interesting to study the pion transverse momentum distribution and the rapidity distribution in symmetric systems to test the sensitivity of the model to the geometry of the pion absorbing matter. In Fig. 2 the rapidity distribution and the transverse momentum distribution are shown for pions from central collision of La+La at a beam energy of 800 MeV/nucleon. It is seen that both the rapidity and the in-plane transverse momentum distributions are symmetric about the center-of-mass rapidity of 0.6 unit and the transverse momentum distribution has a typical S shape.

In order to compare the model predictions and the experimental data of the pion transverse momentum distribution, we have made a full simulation of the detector acceptance of the DIOGENE Collaboration. In the same way as in the experimental data analysis [2], we estimate the reaction plane for each event from the beam direction and the vector

$$\mathbf{Q}_j = \sum_{i \neq j} w_i \mathbf{p}_{\perp i} \tag{20}$$

determined from the detected protons. Here the weights are $w_i = y_i - \bar{y}$, and $\bar{y}$ is the average rapidity of the detected protons. This weight is different from the one that was originally proposed for symmetric systems since the center-of-mass rapidity of the participant system is not known *a priori* in each event for asymmetric nucleus-nucleus collisions. The transverse momentum of a particle j in the estimated reaction plane is defined as

$$p_{xj} = \{\mathbf{Q}_j \cdot \mathbf{p}_{\perp j} / |\mathbf{Q}_j|\} \ . \tag{21}$$

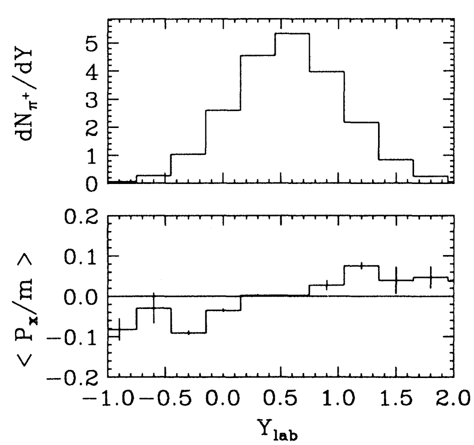

FIG. 2. Rapidity distribution and transverse momentum distribution calculated for La+La reaction at $E/A = 800$ MeV and the impact parameter of 1 fm.

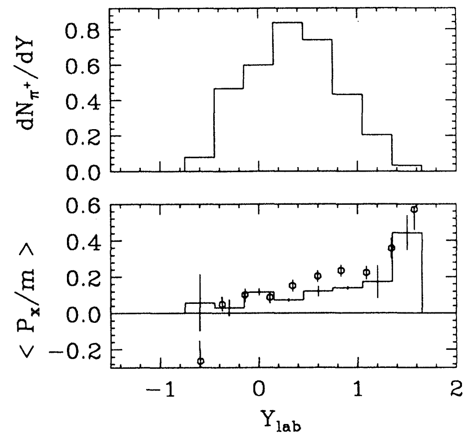

FIG. 3. Upper figure: calculated π^+ rapidity distribution after using the detector filter cut for the Ne+Pb reaction at $E/A = 800$ MeV. Lower figure: comparison between the experimental pion transverse momentum distribution (round plot symbols) and the model calculation (histogram) for the same reaction.

In Fig. 3 we perform a comparison between the experimental data and the model calculations for the Ne+Pb reaction. The experimental data are represented by the round plot symbols. The solid histograms are the model calculations, the error bars in the model calculations are statistical in nature, since we solve the coupled transport equations for the hadronic matter with a Monte Carlo integration technique. The experimental data are in reasonable agreement with our model predictions. To show the effect of the detector filter cut, the rapidity distribution of the detected π^+'s in the model calculation has been shown in the upper part of Fig. 3.

Since the cascade model did not reproduce the preferential emission of pions, it has been conjectured that in-medium effects and pion production channels involving more than two nucleons could be important in the energy range studied here [2]. However, our calculations indicate that it is not necessary to introduce additional medium effects and many-particle processes beyond the nuclear mean field and the Pauli exclusion principle for final-state nucleons to understand the phenomenon of the preferential emission of pions.

In summary, we performed hadronic transport model calculations of the pion rapidity distribution and the in-plane transverse momentum distribution. We discussed the effects of the target shadowing and the Δ flow in forming the positive in-plane transverse momentum of pions in asymmetric nucleus-nucleus collisions. We found that the mechanism for the preferential emission of pions from the interaction zone toward the projectile side in the transverse direction is due to the stronger reabsorption of pions by the heavier target. The model prediction of the pion in-plane transverse momentum distribution agrees with the experimental data. Other transport approaches that include proper treatment of pion and Δ emission and absorption as well as the correct description of the phase space geometry should also be able to reproduce the experimental data. At present, we have no explanation why the cascade [2] and the quantum-molecular-dynamics [5] models fail to do so.

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[1] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).
[2] J. Gosset, O. Valette, J. P. Alard, J. Augerat, R. Babinet, N. Bastid, F. Brochard, N. De Marco, P. Dupieux, Z. Fodor, L. Fraysse, P. Gorodetzky, M. C. Lemaire, D. L'Hôte, B. Lucas, J. Marroncle, G. Montarou, M. J. Parizet, J. Poitou, C. Racca, A. Rahmani, W. Schimmerling, and Y. Terrien, Phys. Rev. Lett. **62**, 1251 (1989).
[3] D. Keane, D. Beavis, S. Y. Chu, S. Y. Fung, W. Gorn, Y. M. Liu, G. VanDalen and M. Vient, in *Proceedings of the 4th Nuclear Dynamics Workshop, Copper Mountain, Colorado, 1986,* edited by V. Viola (Indiana University Report CONF-860270, UC-34C, INC-40007-37, 1986).
[4] P. Danielewicz, H. Stroebele, G. Odyniec, D. Bangert, R. Bock, R. Brockmann, J. W. Harris, H. G. Pugh, W. Rauch, R. E. Renfordt, A. Sandoval, D. Schall, L. S. Schroeder, and R. Stock, Phys. Rev. C **38**, 120 (1988).
[5] C. Hartnack, H. Stöcker, and W. Greiner, in *Proceedings of the International Workshop on Gross Properties of Nuclei and Nuclear Excitation XVI, Hirschegg, Austria, 1988,* edited by H. Feldmeier (Technische Hochschule Report ISSN 0720-8715, Darmstadt, 1988).
[6] B. A. Li and W. Bauer, Phys. Lett. B **254**, 335 (1991).
[7] S. J. Wang, B. A. Li, W. Bauer, and J. Randrup, Ann. Phys. (N.Y.) **209**, 251 (1991).
[8] B. A. Li and W. Bauer, Phys. Rev. C **44**, 450 (1991).
[9] C. Y. Wong, Phys. Rev. C **25**, 1460 (1982).
[10] G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
[11] H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986).
[12] D. Krofcheck, W. Bauer, G. M. Crawley, C. Djalali, S. Howden, C. A. Ogilvie, A. Vander Molen, G. D. Westfall, W. K. Wilson, R. S. Tickle, and C. Gale, Phys. Rev. Lett. **63**, 2028 (1989).
[13] J. J. Molitoris and H. Stöcker, Phys. Lett. B **162**, 47 (1985); J. J. Molitoris, H. Stöcker, and B. L. Winer, Phys. Rev. C **36**, 220 (1987).
[14] G. F. Bertsch, G. E. Brown, V. Koch, and B. A. Li, Nucl. Phys. **A490**, 745 (1988).
[15] J. P. Alard *et al.*, Rapport DPh-N/Saclay Report No. 2583 B.
[16] Particle Data Group, Phys. Lett. B **204**, 1 (1988).
[17] Gy. Wolf, G. Batko, W. Cassing, U. Mosel, K. Nitta, and M. Schäfer, Nucl. Phys. **A517**, 615 (1990).
[18] P. Danielewicz and G. F. Bertsch, Nucl. Phys. A (to be published).