Nuclear Collective Flow and Charged-Pion Emission in Ne-Nucleus Collisions at $E/A = 800$ MeV

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Triple-differential cross sections of charged pions were measured for collisions of Ne projectiles at $E/A = 800$ MeV with NaF, Nb, and Pb targets. The reaction plane was estimated event by event from the light-baryon momentum distribution. For heavy targets, preferential emission of charged pions away from the interaction zone towards the projectile side was observed in the transverse direction. Such a preferential emission, which is not predicted by cascade calculations, may be attributed to a stronger pion absorption by the heavier spectator remnant.

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Nuclear collective flow has already been observed for protons and light nuclei emitted in relativistic nucleus-nucleus collisions.[1-4] Together with other observables such as the pion multiplicity and the deuteron-to proton ratio, it brings an important piece of information towards the determination of the equation of state of highly excited nuclear matter. For that purpose, experimental results have to be compared with more and more sophisticated models[5] which take into account nuclear medium effects. Global variables such as the flow angle and aspect ratios were first used to characterize collective flow on an event-by-event basis. This procedure turned out to be strongly affected by finite-number effects.[6] Later on, Danielewicz and Odyniec proposed the transverse-momentum analysis,[3] which determines the azimuth of an estimated reaction plane on an event-by-event basis. Triple-differential cross sections are then obtained by summing many events and analyzed to measure the characteristics of the flow, with simple corrections for finite-number effects. So far nuclear collective flow has been measured rather extensively for protons and light nuclei. Looking for flow effects in pion emission, we have measured the correlation between the reaction plane, deduced from a transverse-momentum analysis performed on light baryons, and the momenta of charged pions emitted in collisions of neon projectiles on three targets (NaF, Nb, and Pb) at an incident energy per nucleon of 800 MeV. Apart from data obtained for π^- with a streamer chamber,[7] the results reported here are the first measurement of this kind with large statistics, and for both π^+ and π^-.

The experiment was performed at the Saturne synchrotron in Saclay using the pictorial drift chamber (PDC) of the Diogene 4π detector.[8] A barrel-shaped set of thirty plastic scintillator slabs surrounds the PDC. In order to trigger the PDC, at least two of these must be fired, and no beam particle has to be detected downstream from the target. The analysis was made with the PDC and trigger acceptances reported in Table I. The trigger provides a bias against most peripheral collisions and only fragments from the participants system lie in the PDC acceptance. Using the transverse-momentum analysis,[3] we have access to the azimuthal angle φ of the charged pions with respect to an estimated reaction plane, which is defined separately for each event by the direction of the incident beam and the vector $\mathbf{Q} = \sum Z_i w_i \mathbf{p}_{\perp i}/m_i$. The subscript i refers to baryons with atomic number Z_i, transverse momentum $\mathbf{p}_{\perp i}$, and mass m_i. The weight w_i originally proposed in Ref. 3 was $+1$ (-1) for particles with large positive (negative) values of the c.m. rapidity, and 0 for particles with rapidity close to the c.m. rapidity. Since we are not dealing specifically with symmetric systems, the center of mass of the participants system is not known *a priori* for each collision. We have thus replaced the original weight w_i

TABLE I. PDC and trigger acceptances for the present analysis. θ is the polar emission angle, with respect to the beam direction, of a particle with mass m, rapidity y, and transverse momentum $p_\perp$.

	PDC $20° < \theta < 132°$	Trigger $37° < \theta < 119°$	
Pions	$p_\perp/m > 0.66 + 0.77y$	$p_\perp/m > 0.81 + 0.33y$	$y < 0$
	$p_\perp/m > 0.66 - 0.63y$	$p_\perp/m > 0.81 - 0.33y$	$y > 0$
Baryons	$p_\perp/m > 0.36 + 0.72y$	$p_\perp/m > 0.41 + 0.30y$	$y < 0$
	$p_\perp/m > 0.36 - 0.80y$	$p_\perp/m > 0.41 - 0.40y$	$y > 0$

by the continuous function $y_i - \langle y \rangle$, where y_i is the baryon rapidity and $\langle y \rangle = \sum Z_i y_i / \sum Z_i$ is the average rapidity, calculated for each event over all charges carried by the baryons. Triple-differential cross sections for charged pions, in momentum p, polar angle θ, and azimuthal angle φ with respect to the reaction plane, are obtained by adding pions from all events in a given range of $M_{\tilde{p}}$, the multiplicity of protonlike fragments (which combine both free protons and protons bound in light nuclei). Cuts in the $M_{\tilde{p}}$ distribution are used for impact parameter selection. For convenience, the results are presented as a function of the squared reduced impact parameter $b^2/(R_1+R_2)^2$, where b stands for the impact parameter and R_1 and R_2 are the radii of the Ne and target nuclei, respectively. The quantity $b^2/(R_1+R_2)^2$ is estimated, from the $M_{\tilde{p}}$ distribution, as the ratio of the integrated cross section to the geometrical one, with the integration starting from the highest multiplicity bin, and assuming a one-to-one correspondence between increasing impact parameter and decreasing multiplicity.

In order to gain statistics, triple-differential cross sections are reduced to double-differential ones, expressed as a function of the following two variables: rapidity y and transverse momentum (normalized to the particle mass) in the estimated reaction plane $q_{x'} = \hat{\mathbf{Q}} \cdot \mathbf{p}_\perp / m$, where $\hat{\mathbf{Q}}$ is the unit vector along $\mathbf{Q}$. For each rapidity bin, the average value of $q_{x'}$ (denoted as $\langle q_{x'} \rangle_y$) is calculated and its dependence upon rapidity is examined. Figure 1 shows $\langle q_{x'} \rangle_y$ as a function of rapidity for π^+ emitted in Ne+Pb collisions with $b^2/(R_1+R_2)^2 \sim 0.18$, i.e., multiplicity $M_{\tilde{p}}$ ranging from 13 to 17. Results of intranuclear-cascade (INC) calculations[9] in the same impact-parameter range are plotted for comparison. Each event of the INC simulation had to go through the detector filter[10] before being analyzed as an experimental event. Two main results can be seen in Fig. 1. First, and most strikingly, $\langle q_{x'} \rangle_y$ is always positive for the experiment while it is always compatible with zero for INC. One exception for the experiment is the most negative rapidity bin which is strongly affected by the detector cuts, such as the most positive rapidity bin. Charged pions are thus preferentially emitted away from the interaction zone towards the projectile side; this feature is not predicted by INC calculations. Moreover, this behavior is completely different from that observed for protonlike fragments,[3,10] for which $\langle q_{x'} \rangle_y$ is negative or positive according to whether the rapidity is smaller or larger, respectively, than the rapidity of the emitting source. Second, the slope of $\langle q_{x'} \rangle_y$ is rather small and positive in the experiment but compatible with zero in INC calculations. For light baryons, this slope is considered as a measure of the nuclear collective flow. It is not so obvious whether the small slope observed for pions can be attributed to this flow.

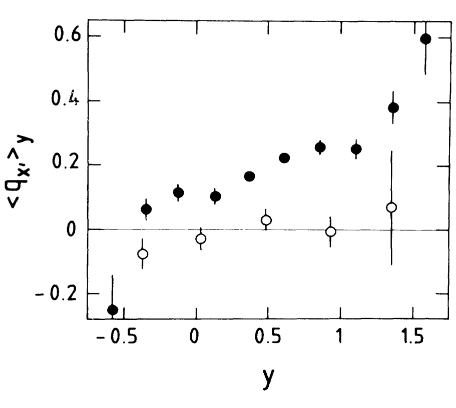

FIG. 1. $\langle q_{x'} \rangle_y$ vs rapidity y for π^+ produced in Ne-Pb collisions at $E/A = 800$ MeV. $q_{x'}$ is the transverse momentum, normalized to the pion mass, in the estimated reaction plane. Experimental results (filled circles) are compared to the results of intranuclear-cascade (INC) calculations (open circles) for collisions with squared reduced impact parameter $b^2/(R_1+R_2)^2 \sim 0.18$.

All our results, similar to Fig. 1 and corresponding to the three targets and all multiplicity bins, have been summarized with three quantities: the global average of $q_{x'}$, the ratio R between the numbers of pions emitted with positive and negative values of $q_{x'}$, and the "flow parameter" F as defined for baryons.[3] The y dependence of $\langle q_{x'} \rangle_y$ is indeed linear; F is the slope S corrected for effects due to the finite number of particles in each event.[3] Since in our experiments we are dealing with rather small multiplicities and shapes not very far from a spherical one,[10] this correction is large and the ratio F/S varies between 1.9 and 2.9. Since the slope is small, a fair measurement of the pion-emission asymmetry in the reaction plane is obtained by the global average of $q_{x'}$, over all values of rapidity, corrected for finite-number effects by the same ratio F/S as above. The result is denoted as $\langle q_x \rangle$ without the prime index since we are referring, after the F/S correction, to the true reaction plane and not to the estimated one. The impact-parameter dependence of $\langle q_x \rangle$ and R is shown in Fig. 2 for both π^+ and π^- emitted in Ne+Pb collisions: The $\langle q_x \rangle$ and R values appear to be strongly correlated and thus carry about the same information. The complete dependences of $\langle q_x \rangle$ and F upon target mass and impact parameter are shown in Fig. 3, for both π^+ and π^-.

The flow parameter F increases with the target mass. For heavy targets, it is a decreasing function of the impact parameter. If interpreted as collective flow, it could be a remnant of the flow carried by the Δ resonances, assumed to follow the same collective behavior as the nucleons. This interpretation is questionable, however, since the cascade model exhibits nonzero values of the F parameter for protons[10] but values compatible with zero (see Fig. 1) for pions, which are all produced through Δ decay in this model. Moreover, as already pointed out by Siemens and Rasmussen,[11] the pions may be a good probe of any hydrodynamical flow, due to their small mass compared to the baryon mass.

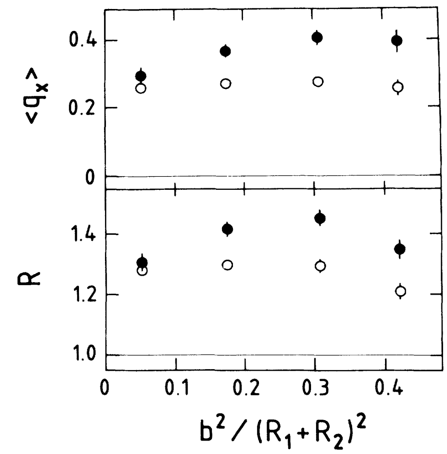

FIG. 2. Impact-parameter dependence of $\langle q_x \rangle$ ($\langle q_{x'} \rangle$ corrected for finite-number effects) and R (ratio between the numbers of pions emitted with $q_{x'} > 0$ and $q_{x'} < 0$) for π^+ (filled circles) and π^- (open circles) produced in Ne-Pb collisions at $E/A = 800$ MeV.

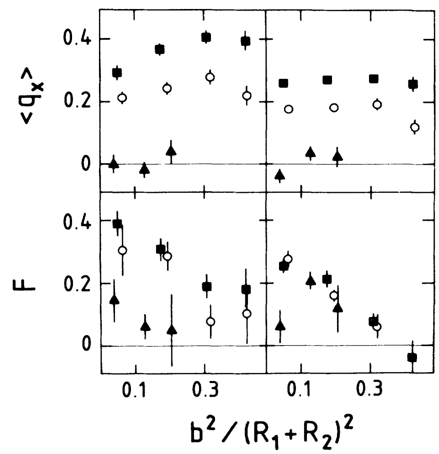

FIG. 3. Impact-parameter dependence of $\langle q_x \rangle$ and flow parameter F for π^+ (left) and π^- (right) produced in Ne collisions with Pb (filled squares), Nb (open circles), and NaF (filled triangles) at $E/A = 800$ MeV.

The following trends are observed for the pion-emission asymmetry. $\langle q_x \rangle$ is compatible with 0, and R with 1, for the NaF target, as they should be for a symmetric system. For heavier targets, $\langle q_x \rangle$ is always positive and R is always larger than 1. The impact-parameter dependence is not very strong. On the contrary, the target dependence is quite strong: $\langle q_x \rangle$ and R increase with the target mass, or the asymmetry of the colliding system, up to values of 0.4 and 1.45, respectively, for π^+ in the case of the Pb target. The detector cuts at small transverse momentum (see Table I) are partly responsible for such high values. The effects are always stronger for π^+ than for π^-, especially for the Pb target at intermediate impact parameter. Most of these results, if not all, can be understood qualitatively as a consequence of stronger pion absorption by the heavier, i.e., target, spectator. Pions are emitted from the participants system where there is enough energy to produce them. On their way out of the interaction zone, they indeed have more nuclear matter to go through when they are emitted towards the heavy target ($q_{x'} < 0$) than towards the light projectile ($q_{x'} > 0$). By looking more closely into the $q_{x'}$ distribution, we also observe that the average modulus of $q_{x'}$ is slightly larger for positive values of $q_{x'}$ than for negative ones, by $(10 \pm 10)\%$, $(6 \pm 10)\%$, and $(0 \pm 10)\%$ for the Pb, Nb, and NaF targets, respectively. This effect, if significant, is smaller than the overall effect measured with R and $\langle q_x \rangle$. It could mean that pions are simply suppressed on the heavy-target side as compared to the light-projectile side, but they keep the same momentum distribution (to the first order at least) on both sides.

As a conclusion, our exclusive measurements of pion production have revealed, for asymmetric systems, a preferential emission of charged pions away from the interaction zone towards the projectile side. This result can be attributed to a stronger pion absorption by the heavier spectator remnant. Such a preferential emission is not predicted by cascade calculations in which pion production and absorption are only mediated by the two-body reactions involving the Δ resonance. In-medium effects could affect these processes. Other channels involving more nucleons may also be important, as indicated in recent π-^{4}He experiments.[12] The same conclusion has been obtained from the analysis of pion production in proton-nucleus collisions.[13] This also means that one has to be very cautious when trying to extract the nuclear-matter equation of state from the difference between experimental and INC results on pion multiplicities in relativistic nucleus-nucleus collisions.[14] The same word of caution has been given by other authors,[15,16] who mentioned other problems in the INC calculations, related to the proper treatment of the binding energy of the nucleons in the nuclei. Finally, more refined models, including mean-field and medium effects, are being developed. They give first hints of pion-emission asymmetry in the reaction plane.[17] The correct propagation of pions and Δ's through the nuclear medium has to be implemented in these models, in order that they reproduce the kind of phenomena reported in this paper. Then they can be used more firmly in view of the determination of the nuclear-matter equation of state.

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