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Global transverse momentum analysis for Ar+KCl and Ar+BaI_2 at 1.2 GeV/nucleon

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High multiplicity collisions of 1.2 GeV/nucleon ^{40}Ar on KCl and on BaI_2 in the Bevalac streamer chamber are studied using the global transverse momentum analysis introduced by Danielewicz and Odyniec. For both systems, there is a sideward flow which is significantly larger than intranuclear cascade model predictions. The current results permit a study of trends in the multiplicity, mass, and energy dependence of the observed flow signatures. Estimates of the stiffness of the nuclear equation of state at high density are discussed.

For many years, it has been recognized that charged particle exclusive data are needed to unambiguously identify and measure fluidlike collective motion in nucleus-nucleus collisions. Until recently, such data have almost invariably been analyzed in terms of the sphericity matrix. For Ca+Ca and lighter symmetric systems, methodologies of this type yield little or no evidence of collective behavior.[1-3] Within the past year, it has been demonstrated that alternative analyses offer much better sensitivity to flow.[4,5] In this Communication, the global transverse momentum analysis introduced by Danielewicz and Odyniec[5] is applied to two data samples resulting from an argon beam exposure at the Bevalac streamer chamber.

The samples under consideration contain a total of 1357 events with charged multiplicity $M \geqslant 30$: 571 collisions with a ^{40}Ar beam incident at 1.2 GeV/nucleon on a KCl target of thickness 0.4 g/cm^2, and 786 collisions with the same beam incident on a BaI_2 target (mean mass number =130) of thickness 0.9 g/cm^2. The chamber was triggered in minimum bias mode;[6] before imposition of the multiplicity cut, the overall sample contained 2320 Ar on KCl events, and 1914 Ar on BaI_2 events. Thus, in the simple geometrical model, the $M \geqslant 30$ cut corresponds to selecting impact parameters < 3.6 (6.0) fm in the case of Ar on KCl (BaI_2). A description of the streamer chamber, the trigger, and particle identification criteria can be found elsewhere.[2,7]

The transverse momentum analysis proposed by Danielewicz and Odyniec[5] involves estimating the reaction plane for each event using

$$\mathbf{Q} = \sum_\nu w_\nu \mathbf{p}_\nu^t \;;$$

$$w_\nu = \pm 1 \text{ for baryons with rapidity } y_{\text{c.m.}} \gtrless \pm\delta \;,$$

$$= 0 \text{ otherwise} \;,$$

where $\mathbf{p}_\nu^t$ is the transverse momentum per nucleon for the νth track. The plotted quantity, $\langle p^{x'} \rangle (y)$, is the mean component of transverse momentum per nucleon in the estimated reaction plane

$$p_\nu^{x'} = \mathbf{p}_\nu \cdot \mathbf{Q}_\nu / Q_\nu, \quad \mathbf{Q}_\nu = \sum_{\mu \neq \nu} w_\mu \mathbf{p}_\mu^t \;.$$

The condition $\mu \neq \nu$ removes the "self-correlation" term from the above scalar product, and thereby avoids one possible type of finite multiplicity distortion. The component in the true reaction plane, p^x, is systematically larger than the component in the estimated plane, $p^{x'}$, hence

$$\langle p^x \rangle = \langle p^{x'} \rangle / \langle \cos\Phi \rangle \;;$$

$$\langle \cos\Phi \rangle \simeq \langle w p^{x'} \rangle [\langle W^2 - W \rangle / \langle Q^2 - \Sigma(w p^t)^2 \rangle]^{1/2} \;,$$

where $W = \Sigma |w|$. Particles close to midrapidity are least likely to be correlated with the event reaction plane, but contribute unwanted statistical fluctuations; a nonzero setting of the parameter δ minimizes these fluctuations (i.e., simultaneously maximizes $\langle p^{x'} \rangle$ and $\langle \cos\Phi \rangle$). For the data used in the present analysis, $\delta \simeq 0.25$–0.30 is the optimum region. An alternative method of estimating $\langle \cos\Phi \rangle$, which involves randomly partitioning each event into two subevents,[5] yields consistent results.

Figures 1(a) and 1(b) show $\langle p^{x'} \rangle (y)$ for the Ar on KCl events, divided between two multiplicity intervals. The predictions of Cugnon's intranuclear cascade model,[8] appropriately filtered to simulate the experimental conditions, are also plotted. Figure 1(c) shows $\langle p^{x'} \rangle (y)$ for Monte Carlo events generated by randomly selecting tracks from different observed events. The null result for the Monte Carlo calculation demonstrates that the significant sidewards de-

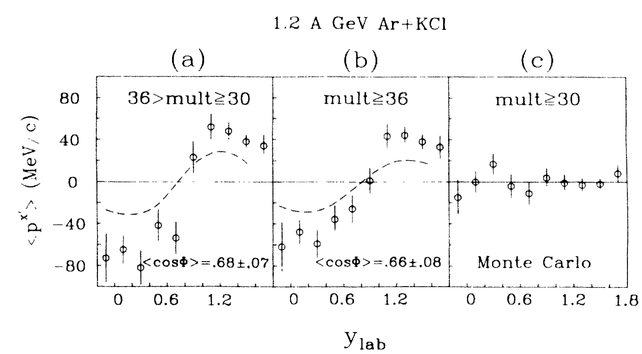

FIG. 1. (a) and (b) Mean transverse momentum per nucleon in the estimated reaction plane, as a function of rapidity, for a total sample of 571 Ar+KCl events. The events are about equally divided between the two multiplicity intervals. The dashed curves are the predictions of Cugnon's cascade code, filtered to simulate experimental conditions. The statistical errors on these predictions are negligible compared with the experimental error bars. The $\langle \cos\Phi \rangle$ values for the cascade events are consistent with the quoted experimental estimates. (c) The same plot for Monte Carlo events generated by randomly selecting tracks from different observed events.

flection in Figs. 1(a) and 1(b) (for both experiment and cascade) is due to correlations within the events, and cannot be the result of detector biases or finite multiplicity effects.

Figure 2 shows $\langle p^{x'} \rangle (y)$ for the Ar on BaI_2 events, binned in three multiplicity intervals, along with the intranuclear cascade predictions. Even for this asymmetric system, the optimum zero-weight rapidity interval does not change significantly with multiplicity, and tracks satisfying $0.8 > y_{lab} > 0.2$ have been assigned $w = 0$ throughout the entire sample. As in the case of the symmetric system, a flat distribution consistent with zero is obtained for Monte Carlo events constructed by randomly selecting tracks from different observed events.

Besides collective flow, the correlation induced by momentum and energy conservation can influence the mean transverse momentum in the true reaction plane, $\langle p^x \rangle$, but has thus far been neglected. Danielewicz and Odyniec have found that the terms[9] to correct for this effect are negligible in the context of their previous analysis[5] of Ar on KCl at 1.8 GeV/nucleon, but they point out that a larger correction is expected in the case of an asymmetric system. Averaged over the Ar on BaI_2 events in the current study, we find that the correction increases $\langle p^x \rangle$ by about 5%, an amount smaller than the statistical errors; it is a 1% effect for the current 1.2 GeV/nucleon Ar on KCl events.

Some variation of flow as a function of impact parameter, b, is to be expected, with maximum sideward flow at intermediate b, and zero sideward flow at $b = 0$. Impact parameter is in turn correlated with total multiplicity. The data for Ar on KCl show no detectable variation of $\langle p^{x'} \rangle$ or $\langle p^x \rangle$ with multiplicity. For Ar on BaI_2, $\langle p^{x'} \rangle$ at forward rapidities shows an upward trend with increasing multiplicity. When expressed in terms of $\langle p^x \rangle$, the transverse flow in the true reaction plane, this variation persists but is of marginal statistical significance.

Figures 1 and 2 demonstrate a significant increase in measured $p^{x'}$ and p^x with increasing target mass. The same tendency is evident for cascade events. Comparison of the Ar on KCl data with results of a preliminary analysis[10] of U on U events at similar energy indicates that p^x also increases with total mass in symmetric systems.

Comparison of the current findings with the streamer chamber results reported by Danielewicz and Odyniec[5] indicates a 40%–50% increase in both $\langle p^{x'} \rangle$ and $\langle p^x \rangle$ for Ar on KCl between 1.2 and 1.8 GeV/nucleon. The data at 1.8 GeV/nucleon were collected using a central collision trigger,

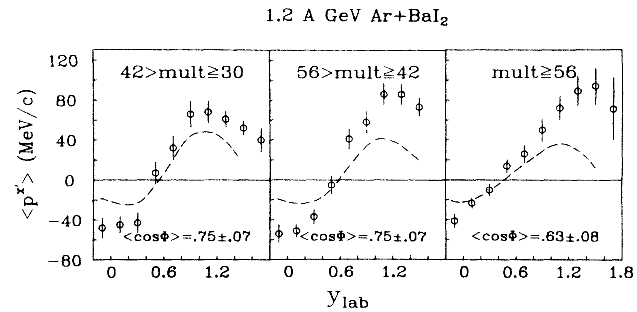

FIG. 2. As Figs. 1(a) and 1(b), but for a total sample of 786 $Ar + BaI_2$ events, divided equally between three multiplicity intervals.

as opposed to a minimum bias trigger combined with a multiplicity cut for the 1.2 GeV/nucleon data in the present study. By imposing a cut on the 1.2 GeV/nucleon data which is equivalent to a central collision trigger, we conclude that the differences in the sample selection criteria can account for no more than a minor part of the observed change in $\langle p^x \rangle$ (see Table I). A previously reported[2] sample of Ar on Pb collisions at 0.4 GeV/nucleon has been reanalyzed using the transverse momentum method; the $\langle p^x \rangle$ values obtained[11] are ~60% of those for Ar on BaI_2 at 1.2 GeV/nucleon.

Although Cugnon's intranuclear cascade model exhibits trends in mass and energy dependence that are similar to the experimental results, it consistently underpredicts the overall magnitude of $\langle p^{x'} \rangle$ and $\langle p^x \rangle$, particularly at the highest multiplicities. Most theoretical studies[12–15] indicate that cascade models yield little or no collective flow, and attribute underpredictions of flow to the absence of nuclear compressional energy in this model. The cascade code of Kitazoe *et al.*[16] generates a relatively large flow signature, and can reproduce flow angle distributions for 0.4 GeV/nucleon Nb on Nb, as observed at the plastic ball;[3] however, this code assumes that the residual nuclei maintain constant density, a feature that Molitoris *et al.*[15] argue is unphysical and a source of spurious flow.

Molitoris and Stöcker[14] have adopted the approach of the Vlasov-Uehling-Uhlenbeck (VUU) equation in order to treat nuclear compressional effects in a microscopic theory which incorporates cascadelike nucleon pair collisions with appropriate Pauli blocking. They have found that the

TABLE I. Observed $\langle p^x \rangle_{max}$ in MeV/c for Ar on KCl at 1.8 GeV/nucleon (495 events, Ref. 5) and at 1.2 GeV/nucleon (571 events, this experiment); some model predictions are also shown.

		1.8 GeV/nucl	1.2 GeV/nucl
Experiment, central trigger		100	~75
Experiment, min. bias, $M \geqslant 30$		···	70 ± 10
Cugnon's cascade (filtered)		···	38
VUU [$N(b)db \propto bdb$, $b < 2.4$ fm]	$K = 0$ MeV	25	···
	$K = 200$ MeV	60	50
	$K = 380$ MeV	100	80
VUU [corrected $N(b)$]	$K = 380$ MeV	113	95

predicted peak of $\langle p^x \rangle (y)$ varies linearly with the nuclear compressibility coefficient, K, a finding which underlines the utility of p^x plots in studying the nuclear equation of state. Their predictions for 1.8 GeV/nucleon Ar on KCl, assuming a "stiff" equation of state (density dependent potential $= a\rho + b\rho^c$, $K = 380$ MeV), are in agreement with the experimental results of Danielewicz and Odyniec[5] (see Table I). Table I also shows VUU model predictions for 1.2 GeV/nucleon Ar on KCl;[17] while the $K = 380$ MeV prediction is closer to our experimental result, an equation of state with "medium stiffness" ($K = 200$ MeV) cannot be confidently excluded. Moreover, the impact parameter averaging ($b < 2.4$ fm) used in the VUU predictions is inappropriate for comparison with either the trigger selected or multiplicity selected events. Readjustment of the impact parameter averaging calls for VUU $\langle p^x \rangle$ predictions at various fixed b, but such data are available only for 0.8 GeV/nucleon Ar on Pb;[18] to illustrate the importance of b averaging, we have assumed that $\langle p^x \rangle_{max}$ as a function of b/b_{max} has a similar shape for Ar on KCl, and have used filtered cascade simulations to generate plausible b distributions, thus calculating the corrected $\langle p^x \rangle_{max}$ values at the bottom of Table I. Linear interpolations[14] to fit the experimental data lead to significant reductions in K. Overall, the principal conclusion of Ref. 14—that the 1.8 GeV/nucleon Ar on KCl data are evidence for the stiffer nuclear equation of state—seems premature.

In general, a fit to determine the compressibility coefficient should extend over all regions of the $\langle p^x \rangle (y)$ spectrum where there is some sensitivity to K. The error on $\langle \cos\Phi \rangle$ dominates the statistical uncertainty in such a fit, and so it appears preferable to use transverse momentum in the estimated reaction plane, $p^{x'}$, as the basis for comparisons between models and the experimental data. Comparisons of $p^{x'}$ for the currently available samples with appropriately filtered VUU model predictions ought to yield useful estimates of the stiffness of the nuclear equation of state.

In summary, results of a global transverse momentum analysis are presented for two samples of high multiplicity events from the Bevalac streamer chamber: Ar on KCl and Ar on BaI_2, both at an incident energy of 1.2 GeV/nucleon. In each case, nontrivial correlations indicative of collective sideward flow are observed. The mean transverse momentum per nucleon in the event reaction plane, p^x, does not vary significantly with multiplicity over the range studied. Comparisons with other data indicate that p^x increases with beam energy, and with the mass of the colliding system. The intranuclear cascade model yields a significant flow signature, which follows trends similar to the experimental data, but is consistently smaller. The experimental data for Ar on KCl have been compared with preliminary predictions of a microscopic model incorporating a repulsive nuclear equation of state at high densities. More detailed comparisons with the existing data have the potential to provide valuable information about the compressibility coefficient ("stiffness") of the equation of state.

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