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Measurement of kinetic flow parameters for relativistic collisions of Ne on NaF and Ar on Pb_3O_4

D. Beavis, S. Y. Chu, S. Y. Fung, W. Gorn, A. Huie, D. Keane, J. J. Lu, R. T. Poe, B. C. Shen, and G. VanDalen
Department of Physics, University of California at Riverside, Riverside, California 92521
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We present kinetic flow parameters based on charged particle exclusive streamer chamber data for Ne on NaF at bombarding energies of 0.425 GeV/nucleon and 0.577 GeV/nucleon, and for Ar on Pb_3O_4 at 0.4 GeV/nucleon. Flow angles and aspect ratios are determined as functions of charged track multiplicity. The experimental findings are compared with predictions based on the intranuclear cascade model of Cugnon *et al.*

[NUCLEAR REACTIONS ^{20}Ne(NaF), $E_{lab}=0.425$, 0.577 GeV/nucleon, ^{40}Ar(Pb_3O_4), $E_{lab}=0.4$ GeV/nucleon. Global analysis, comparison with intranuclear cascade model.]

Despite the greatly improved understanding of nucleus-nucleus interactions that has resulted from single particle inclusive experiments at relativistic energies, some fundamental issues remain unresolved—among them, the question of whether interacting nuclei behave like a dilute gas or a fluid at these energies. It is now widely acknowledged that the charged particle exclusive data provided by 4π detectors are needed to resolve such questions. However, there is as yet no clear consensus regarding the optimum method of analysis of exclusive data. Various approaches[1] which have been used to characterize event shapes in high energy physics are possible candidates, as are simple laboratory frame variables such as longitudinal energy fraction[2] or transverse rigidity,[3] as used in the first total event analysis of a large sample of relativistic heavy ion collisions.

Recently, Gyulassy, Frankel, and Stocker have proposed a global analysis in terms of kinetic flow,[4] an approach which is adapted to the special needs of heavy ion physics. The purpose of this Communication is to present kinetic flow parameters determined from three experimental samples which are the largest of their kind currently available. We also discuss various measures taken to minimize potential biases in the data, and we suggest cuts in the spectator regions to allow a more effective comparison between theory and experiment.

In the kinetic flow methodology, an ellipsoidal event shape is associated with a kinetic flow tensor F constructed from a set of measured final momenta in the center-of-mass (c.m.) frame:

$$F_{ij}=\sum_{\nu=1}^{N} P_i(\nu)P_j(\nu)/2m_\nu \ .$$

This definition is "coalescence invariant," i.e., the contribution of a composite fragment of mass number A is the same as that of A free nucleons with the same energy per nucleon. To quantify nuclear flow in exclusive data analysis, Gyulassy *et al.* have suggested ordering the eigenvalues f of the kinetic flow tensor such that $f_1>f_2>f_3$, and plotting the kinetic flow aspect ratios f_1/f_3 and f_2/f_3 against θ_1, the polar angle of maximum kinetic flow. This prescription will reveal whether any special ellipsoidal event shape is favored. Theoretical models which incorporate collective effects such as hydrodynamic flow predict event shapes that differ from intranuclear cascade results (in particular, they predict larger flow angles), and these differences become more pronounced with increasing number of participant nucleons.[4]

The three streamer chamber data samples under consideration contain 4417 events corresponding to 0.425 GeV/nucleon Ne incident on a 1.43 g/cm^2 NaF target, 793 events corresponding to 0.577 GeV/nucleon Ne on the same target, and 427 events resulting from 0.4 GeV/nucleon Ar on a 1.17 g/cm^2 Pb_3O_4 target. The kinetic flow angle θ_1, and the flow aspect ratios f_1/f_3 and f_2/f_3, are presented as functions of positively charged track multiplicity, which serves as an additional constraint in comparing theory with experiment. Moreover, the dependence of kinetic flow on impact parameter is of considerable interest, and Cugnon and L'Hote[5] have demonstrated that the cascade model predicts participant multiplicity to be the best experimental observable with which to select a narrow range of impact parameters.

To facilitate comparisons between theory and experiment, two categories of tracks have been excluded. The first category contains low rigidity tracks:

< 0.25 GV/c for the Ne on NaF samples, and < 0.2 GV/c for the Ar on Pb_3O_4 sample. This cut excludes tracks in the region where energy loss and absorption in the target material have a significant effect on rigidity spectra. A higher cutoff rigidity would be more appropriate for tracks close to $\theta = 90°$; however, the number of missing tracks in this region with rigidity above the cutoff (estimated by interpolation) is too small to bias the multiplicity distributions or flow patterns. The second cut excludes tracks with $\theta < 5°$. Measurements of ionization[6] within $\theta < 20°$ indicate that most multiple-charge fragments lie at $\theta < 5°$, and most of the relatively small number of $Z \geq 2$ tracks in the range $5° \leq \theta < 20°$ are consistent with $Z = 2$. These measurements, as well as inclusive data,[7] indicate that the positive track multiplicity after cuts, N'_+, can be treated as a coalescence-invariant variable like the kinetic flow angle and aspect ratios. Typically, the cuts remove about two tracks per event from the Ne on NaF samples, and about three tracks per event from the Ar on Pb_3O_4 sample; these numbers do not vary appreciably with multiplicity.

With decreasing multiplicity, the flow patterns approach the trivial case for noninteracting projectiles. We have confined our attention to Ne on NaF events with $N'_+ \geq 9$, and Ar on Pb_3O_4 events with $N'_+ \geq 11$. In the case of the 0.425 GeV/nucleon Ne on NaF sample, this multiplicity cut has allowed central trigger data to be combined with inelastic trigger data with minimal chance of the flow plots being affected by trigger bias.[3] In fact, comparison of the separate flow plots for inelastic and central trigger data confirms both excellent agreement above $N'_+ \simeq 9$, and an increasing discrepancy below this multiplicity. The final number of events in each sample, after satisfying criteria to ensure data integrity, and applying multiplicity cuts, is 1651 for 0.425 GeV/nucleon Ne on NaF, 145 for 0.577 GeV/nucleon Ne on NaF, and 183 for Ar on Pb_3O_4.

In order to transform momenta into the c.m. frame and to calculate kinetic flow, it is necessary to assign a mass to each particle. In the absence of explicit particle identification at the streamer chamber, we have used phase space considerations and the coalescence power law[7] to correct our results for the presence of $Z = 1$ composite fragments among the final state particles. If the condition for coalescence of two fragments is that their relative velocity should be close to zero, then for emission of a fragment of mass number A, and momentum $P_A = AP_{A-1}$, the coalescence coefficient

$$C_A = \rho_A / (\rho_{A-1})^A ,$$

where

$$\rho_A = E_A d^3\sigma_A / d^3P_A ,$$

should be independent of the fragment momentum and angle. Several experiments[7] have shown the inclusive light fragment spectra for $\theta \geq 10°$ to be in excellent agreement with this coalescence power law.

We have assumed that at fixed multiplicity, C_A is still independent of the fragment momentum and angle. The values of C_A for deuterons and tritons were determined from the rigidity distributions near $\theta = 10°$; fragments in this region have velocities close to that of the incident beam, resulting in distinct, minimally overlapped rigidity distributions for protons, deuterons, and tritons.[3] At larger angles, these C_A values allow the proton, deuteron, and triton spectra to be extracted from the observed rigidity distributions. This in turn permits a Monte Carlo generated identity to be assigned to each track in a region of overlapping rigidity spectra, the probability being appropriately weighted according to the angle and rigidity of the track, and the multiplicity of the event. We present kinetic flow patterns averaged over the events in a multiplicity interval, and the uncertainties in the flow plots arising from the Monte Carlo corrections for composite fragments are negligible compared to the statistical errors.

Figure 1(a) shows the flow diagrams for the two Ne on NaF data samples.[8] The number that labels each point is the center of the N'_+ multiplicity interval. To indicate the sensitivity of the results to the corrections for composite fragments, we show flow plots corresponding to the assumption that all fragments are protons. No statistically significant difference between the Ne on NaF flow patterns at energies of 0.425 and 0.577 GeV/nucleon can be detected.

In the Ar on Pb_3O_4 sample, the number of Ar on O interactions can be neglected above $N'_+ \sim 15$ to 20. For Ar on Pb interactions, the analysis is complicated by the fact that no single Lorentz frame satisfies the requirement that the ellipsoid should be centered at the origin for all multiplicities. In Figs. 1(b) and 1(c), we show flow diagrams for the c.m. frame appropriate to clean-cut geometry at zero impact parameter, and for the nucleon-nucleon c.m. frame. As expected, these two frames correctly center the ellipsoids (within small fluctuations) at high and low multiplicities, respectively. The very significant differences between Figs. 1(b) and 1(c) illustrate the importance of correct center alignment.

We have also investigated flow patterns for events generated using the cascade code of Cugnon *et al.*[9] This code does not incorporate a nuclear potential or composite fragment production, and predicts transverse momenta per nucleon in the spectator regions that are much greater than experimentally observed values[10]; only a small percentage of the noncolliding nucleons are excluded by the same rigidity and angular cuts as imposed on the experimental data. In order to bring the predicted and observed N'_+ distributions for Ne on NaF into agreement over the entire N'_+ spectrum, at least some cascade specta-

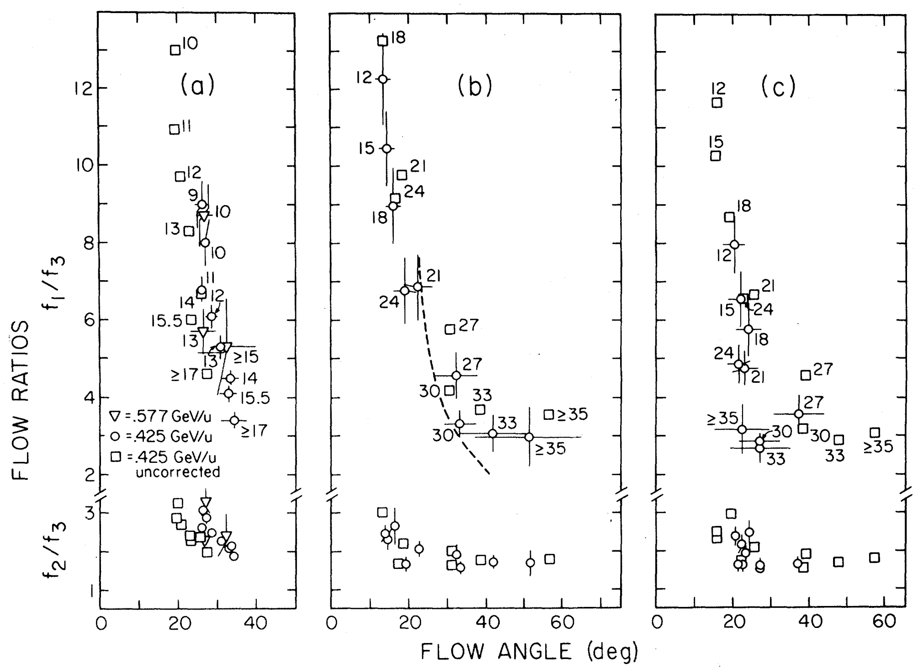

FIG. 1. (a) Kinetic flow diagrams for the Ne on NaF data. The numbers labeling the points denote the multiplicity, N'_+. To avoid clutter, the multiplicity labels and the horizontal error bars have been omitted from the f_2/f_3 plot; this information can readily be obtained by reference to the corresponding points in the f_1/f_3 plot. The squares denote the flow pattern corresponding to the 0.425 GeV/nucleon data uncorrected for composites. (b) Kinetic flow plots for the Ar on Pb_3O_4 data in the Lorentz frame appropriate to clean-cut geometry at zero impact parameter; otherwise as (a). The dashed line shows the upper limit of flow angle as a function of f_1/f_3, as predicted by the cascade code of Cugnon *et al.* (c) Kinetic flow plots for the Ar on Pb_3O_4 data in the nucleon-nucleon c.m. frame.

tors must be excluded. Exclusion of all cascade spectators results in satisfactory agreement. The f_1/f_3 flow plot for Ne on NaF cascade events[11] parallels the experimental data, with a constant difference in flow angle; with spectators present, the flow angle lies about 15° below the experimental data, while with spectators excluded, the cascade flow angle shifts to about 15° above the observed values. These results do not rule out the possibility of the cascade predictions coming into agreement with the Ne on NaF data, given a more sophisticated treatment of spectator nucleons. However, the fact that the cascade flow patterns are subject to such uncertainty emphasizes the need for caution in using differences between experiment and cascade predictions as a signature of collective effects.

In the light of the findings for Ne on NaF, we have calculated cascade flow patterns for Ar on Pb both with and without spectators, and have also examined intermediate cases. The flow angle as a function of the aspect ratio f_1/f_3 for any value of N'_+, and for any assumption about spectators, does not exceed the values indicated by the dashed line in Fig. 1(b), and has a consistently smaller $|d\theta_1/d(f_1/f_3)|$ than the experimental plot.

In summary, we present a study of total event structure using the kinetic flow methodology. The flow parameters which we have measured can serve as strong constraints in appraising and refining theoretical models. The imposition of cuts on the data facilitates comparisons between any theoretical model and experiment, and we emphasize that these cuts can easily be incorporated in theoretical calculations. The differences between the observed kinetic flow for Ar on Pb and the predictions of the cascade code of Cugnon *et al.* are qualitatively consistent with the hypothesis that collective behavior occurs. A more definite conclusion about collective effects using the approach adopted in this Communication appears to demand a detailed treatment of spectator nucleons in the cascade model.

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[8]D. Keane *et al.*, in Proceedings of the International Conference on Nucleus-Nucleus Collisions, East Lansing, Michigan, 1982 (unpublished), p. 89. In this conference abstract, we presented preliminary kinetic flow plots based on some of the present data; because angle and rigidity cuts were not applied, smaller flow angles were obtained at low multiplicity. The cuts have relatively little effect at high multiplicity.

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[10]D. E. Greiner *et al.*, Phys. Rev. Lett. 35, 152 (1975); H. H. Heckman *et al.*, Phys. Rev. C 17, 1735 (1978).

[11]Throughout the cascade calculations, an appropriate fraction of the final-state nucleons has been ignored so as to simulate the nonobservation of free neutrons. In disagreement with Gyulassy *et al.* (Ref. 4), we have found that inclusion of all nucleons significantly alters the flow patterns.