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Identification of collective flow by transverse-momentum analysis of emulsion data for Au + AgBr and Xe + AgBr

L. P. Csernai,[*] P. Freier, J. Mevissen, H. Nguyen, and L. Waters[†]
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

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Transverse-momentum data are analyzed for the presence of collective flow of nuclear matter in interactions of Au and Xe in nuclear emulsion at energies from 0.5 to 1.2 GeV/nucleon. Evidence of such flow is obtained from 122 interactions involving AgBr in nuclear emulsion by adapting a recently proposed method of transverse-momentum analysis.

I. INTRODUCTION

One of the most important discoveries of relativistic heavy ion physics is the detection of collective sideward flow.[1] Its accurate measurement provides probably the best means so far to track down collective nuclear properties. Recently, a new method was introduced[2] which minimizes random statistical fluctuations and makes it possible to evaluate quantitatively the average momentum of the collective transverse flow from streamer chamber data.

Although the existence of sideward flow was predicted and analyzed by fluid-dynamical calculations for a long time,[3] previously there was some doubt as to experimental evidence concerning the sidewards flow. Similarly, there was a general opinion that, even if it did exist, it would not be possible to measure the sidewards flow in emulsion experiments because of the lower statistics, even though sidewards flow first was claimed to be seen in emulsion-type silverchloride track detectors.[4] We want to demonstrate that, due to recent developments in evaluating the experimental data, the possibilities of emulsion experiments should be reconsidered.

II. DESCRIPTION OF THE METHOD

We adapt the transverse momentum analysis method proposed by Danielewicz and Odyniec[2] to detect the presence of collective flow from interactions of $^{197}_{79}$Au and $^{132}_{54}$Xe in nuclear emulsion. 54 (74) interactions involving 654 (524) fragments resulting from a 1.0 (1.2) GeV/nucleon Au (Xe) beam obtained at the Bevalac are analyzed.[5] The energy of the projectile at the interaction in the emulsion is smaller than the incident beam energy. The energy of the interacting projectile is determined by range measurements, and only those events are selected for analysis where the projectile energy falls between 0.5–1.0 GeV/nucleon ($\langle E_{\mathrm{Au}} \rangle = 734$ MeV, $\sigma_E = 137$ MeV) for the Au beam and 0.8–1.2 GeV/nucleon ($\langle E_{\mathrm{Xe}} \rangle = 1059$ MeV, $\sigma_E = 81$ MeV) for the Xe beam. At these energies there is a clear distinction between target (ta) particles and projectile (pr) fragments. It is important to consider all composite fragments in the flow analysis,[6] so all projectile fragments μ with Z_μ greater than or equal to 2 are identified through their ionization. The mass of a fragment of charge Z_μ is assumed to be $A_\mu = 2Z_\mu$. The number of target particles (N_h) are measured for each event, and only events with N_h greater than or equal to 8, i.e., representing a Ag or Br target, are considered in the analysis. Furthermore, we only study interactions with three or more helium nuclei emitted. The relative number of such events to the total AgBr interactions is 64% for Au and 60% for Xe; hence these two selection criteria correspond approximately to an impact parameter cut at about 0.8 ($R_{\mathrm{pr}} + R_{\mathrm{ta}}$).

The polar and azimuthal angles of all projectile fragments with respect to the projectile are measured with an accuracy of about 3 mrad. Since the collisions analyzed have different projectile energies, E_{pr}, the laboratory polar angle, θ, distributions are not the same. To circumvent this energy dependence, we introduce the pseudo-transverse-momentum, which is expected to be less energy dependent that θ. The pseudo-transverse-momentum per nucleon, $\mathbf{p}^t_\mu$, for each projectile fragment μ is defined by assuming that the fragment had the same longitudinal momentum per nucleon $P_{\parallel} = P_{\mathrm{pr}}/A_{\mathrm{pr}}$ as the incident projectile of mass A_{pr}, i.e.,

$$P^t_\mu = \tan\theta_\mu P_{\parallel} ,$$

and it points in the azimuthal direction of the emitted fragment.

Figure 1 presents a histogram of the P^t_μ thus obtained for $Z = 2$ and $Z > 2$ fragments for Au + AgBr reactions. The mean pseudo-P^t for the helium fragments is 189 (MeV/c)/nucleon, while for heavier fragments it is 115 (MeV/c)/nucleon. To show that the dependence of pseudo-P^t on projectile energy is small, we compare the upper and lower half of the energy range. The mean of the upper/lower half of the considered projectile energy range deviates from the total mean only by $+6.8/-8\%$ for helium fragments and by $+15/-17\%$ for other fragments.

For every interaction the mean value of pseudo-P^t per nucleon projected onto the reaction plane,[2] $\langle P^{x'}_\mu / A_\mu \rangle$, is evaluated in the following way. The momentum components of each projectile fragment P^t are projected on the reaction plane,

$$P^{x'}_\mu / A_\mu = \mathbf{P}^t_\mu \mathbf{Q}_\mu / | Q_\mu | ,$$

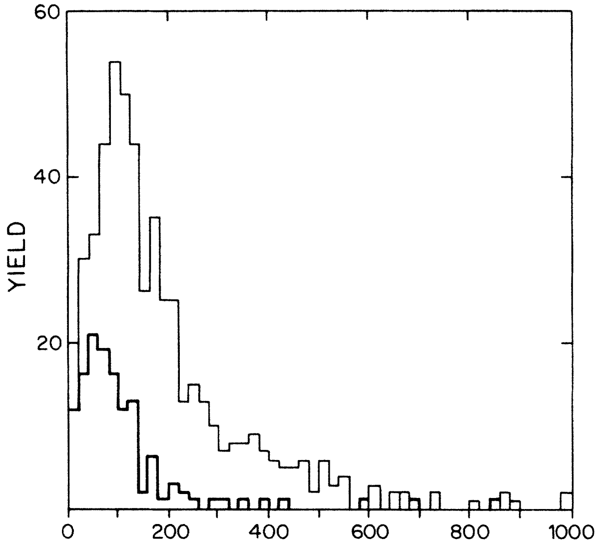

FIG. 1. The distribution of pseudo-transverse momentum P^t of the emitted $Z=2$ (thin line, 520 particles) and $Z>2$ (thick line, 134 particles) projectile fragments from the analyzed 54 events in 0.5–1.0 GeV/nucleon Au + AgBr interactions. The pseudo-P^t is defined from θ by assuming that the projectile fragments keep the rapidity of the beam particle calculated at the interaction.

where the reaction plane is defined by the vector

$$\mathbf{Q}_\mu = \sum_{\nu \neq \mu} w_\nu A_\nu \mathbf{P}_\nu^t$$

(the sum runs over all particles ν of the event, except for the particle μ). In the original work[2] the weight factors w_μ were chosen depending on the rapidity, $y=\text{arctanh}(P_{\parallel}/E)$, of the fragment: $w_\mu = +1$ for fragments with center of mass rapidity greater than some $y_{\text{c.m.}}+d$, $w_\mu = -1$ for center of mass rapidity less than $y_{\text{c.m.}}-d$, and $w_\mu = 0$ otherwise. The value of d was chosen to eliminate particles from the mid rapidity region which contribute to unwanted fluctuations in the determination of the reaction plane. We do not determine the rapidity of fragments in the emulsion, so we must modify the cutting procedure. Particles moving forward, backward, and close to c.m. rapidity should have been separated according to the original method.[2] In emulsions it is preferable to eliminate both the mid rapidity and the backward going (target) particles, because of inherent difficulties in accurate measurement of the latter. This leaves us only the forward going particles (which have small pseudo-P^t) to determine the reaction plane. Thus we define the cuts in terms of the pseudo-P^t, which already includes the dependence on the energy of the projectile:

$$P_{\text{cut}}^t = \tan\theta_{\text{cut}} P_{\parallel} \; .$$

We assign weights of 0 to fragments with pseudo-P^t greater than some given value, + 1 to all others. We note that the analysis will not be effective for events in which less than four fragments survive this cut; we therefore exclude two such events from the 54 in the case of the Au beam and four events of the 74 in the case of the Xe beam. We seek to maximize the mean value of $\langle P^{x'}/A \rangle$ of all events and minimize the dispersion of this value. A cut at pseudo-$P_{\text{cut}}^t = 280$ (MeV/c)/nucleon was found to be the best.

Since we cannot measure the rapidity of the emitted fragments, we can define pseudorapidity, polar angle, or pseudo-P^t bins. Now bins containing small pseudo-P^t correspond essentially to fragments of high rapidity, while those at larger pseudo-P^t correspond to rapidity bins around $y_{\text{c.m.}}$ and target rapidities.

III. ANALYSIS OF THE Au + AgBr DATA

The mean value of $\langle P^{x'}/A \rangle$ for all 52 Au + AgBr events is plotted in Fig. 2 for different pseudo-P^t bins: 0–50, 50–150, 150–250, and 250–500 MeV/c. The maximum of the distribution is 63 ± 16 MeV/c, found to be at pseudo-$P^t = 200$ (MeV/c)/nucleon. The general dependence of $\langle P^{x'}/A \rangle$ over y (in our case, on the corresponding pseudo-P^t bins) is consistent with the recent results of the streamer chamber experiments.[7]

To investigate if such a parameter represents a significant flow of transverse momentum, we made a Monte Carlo analysis of the 54 events. 54 Monte Carlo events were generated by randomly distributing the 654 fragments among the generated events. The distribution of the mean $\langle P^{x'}/A \rangle$ versus the pseudo-P^t bins for 100

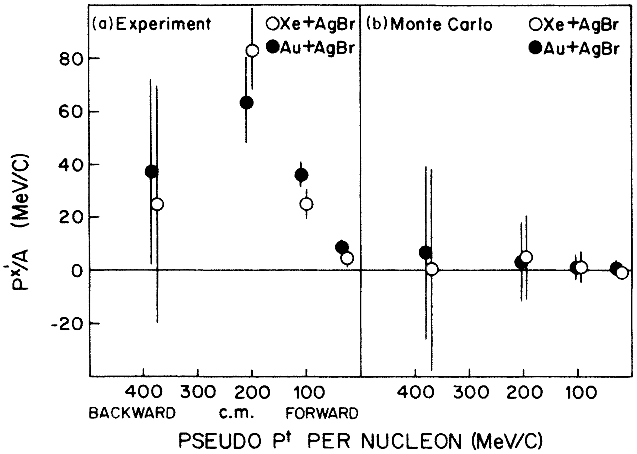

FIG. 2. (a) The mean transverse momentum projected into the reaction plane $\langle P^{x'}/A \rangle$ for emitted particles falling in different pseudo-transverse momentum bins. Bins with small pseudo-P^t essentially correspond to forward going fragments in the c.m. system, i.e., $y > y_{\text{c.m.}}$. Bins with large pseudo-P^t [$P^t > 400$ (MeV/c)/nucleon] correspond to particles moving backward in the c.m. frame. The forward going particles are emitted sidewards, azimuthally correlated with each other by the collective flow. The points represent bin averages; the Au + AgBr and Xe + AgBr points are plotted apart only to facilitate their recognition. (b) Same as (a), but for the events generated by Monte Carlo simulation from the original sample. The analysis shows that the randomized events do not show the collective sideward flow.

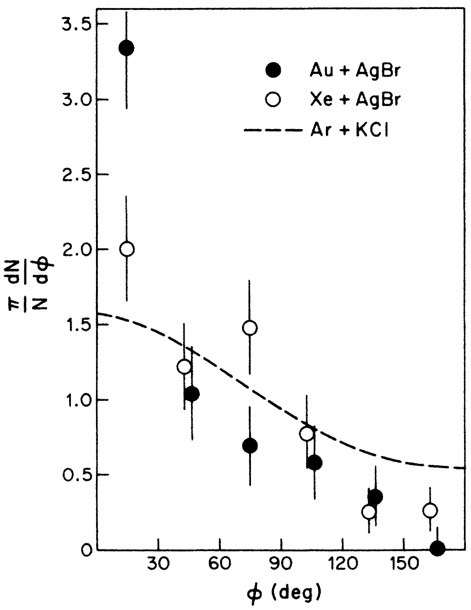

FIG. 3. The distribution of the difference of the azimuth angles of the reaction planes determined from the two halves of every event. The peak at zero indicates that the two reaction planes are correlated. The dashed line represents the 1.8 GeV/nucleon Ar + KCl data from Ref. 2. Our data show a stronger correlation due to the heavier systems studied and to the fact that only heavy emitted fragments ($Z \geq 2$) were considered to diminish thermal fluctuations (Ref. 6).

Monte Carlo runs is shown in Fig. 2(b). The largest mean of Monte Carlo $\langle P^{x'}/A \rangle$ values is 3.9 MeV/c, i.e., it does not differ significantly from zero. The error bars indicate the standard deviation of the 100 Monte Carlo runs.

In order to test the accuracy of the estimated reaction plane, we performed the correlation study used by Danielewicz and Odyniec.[2] We estimated the reaction planes from both halves of the particles separately in each event and then we obtained a difference between the azimuth angles of the two estimated planes. The distribution of this difference in azimuth angles peaks sharply at zero (Fig. 3), indicating that the obtained reaction planes are not accidental, but they reflect real physical correlations among the emitted particles. Due to our smaller statistics we used six azimuth angle bins to characterize the azimuth angle difference distribution.

IV. ANALYSIS OF THE Xe + AgBr DATA

In Fig. 2 the mean value of $\langle P^{x'}/A \rangle$ for all 70 Xe + AgBr events is also plotted for the same pseudo-P^t bins as before: 0–50, 50–150, 150–250, and 250–500 MeV/c. The maximum of the distribution is now higher, 83±15 MeV/c, found to be at the same pseudo-P^t of 200 (MeV/c)/nucleon. The general dependence of $\langle P^{x'}/A \rangle$ is the same as in the previous case. The higher transverse momentum is consistent with the higher beam energy in this sample. Now the mean projectile energy at the impact is 1059 MeV/nucleon, compared to the 734 MeV/nucleon for the Au data.

The same type of Monte Carlo analysis that we performed for the gold data confirmed our results. The Monte Carlo events generated by randomly distributing the 504 fragments among the generated events shows a mean $\langle P^{x'}/A \rangle$ distribution versus pseudo-P^t which does not differ significantly from zero.

The reaction plane correlation test (Fig. 3) gave the same result as the Au + AgBr reactions with the experimental error. Thus the two reactions analyzed yield results consistent with each other and both indicate the existence of a correlated transverse momentum flow.

V. SUMMARY

We have shown that our emulsion data exhibit a significant transverse flow, and that the mean value of $\langle P^{x'}/A \rangle$ is significantly different from the Monte Carlo result. The behavior and values of $\langle P^{x'}/A \rangle$ are consistent with streamer chamber[7] data and our maximum $\langle P^{x'}/A \rangle$ falls in the range of the data from 1.2 GeV/nucleon Ar + KCl, 1.8 GeV/nucleon Ar + KCl, and 0.9 GeV/nucleon U + U, where $\langle P^{x'}/A \rangle_{\max}$ approximately equals 45, 120, and 80 MeV/c, respectively. Furthermore, the fact that the transverse momentum increases with increasing beam energy is seen in our emulsion experiments too. The statistics and number of events that were analyzed are similar to those of the streamer chamber data. Thus we have demonstrated that emulsion experiments are an economic and competitive means of analysis of collective flow.

Finally, we want to mention two similar methods developed at the same time. It was suggested by Gustafsson *et al.*[8] recently that an azimuthal correlation method the authors used to analyze Plastic Ball data might also be applicable to emulsion experiments. Although the present work does not use the suggested method, it still confirms their prediction that azimuthal correlations caused by collective flow can be observed in emulsion experiments.

Independently of this work, recently another group identified the collective transverse flow in emulsion experiments.[9] The method used in this work is also different, but qualitatively all show the same effects and the same basic trends in energy and mass dependence. In view of the fact that there are different ways to trace collective flow in emulsion experiments, we would like to mention that the advantage of the method we use is its close relation to the Danielewicz-Odyniec method, which is becoming the standard way of analyzing collective flow. In this way not only the qualitative existence of the flow can be stated, but we can evaluate quantities (like $\langle P^{x'}/A \rangle$) which can be compared to the values extracted in experimental techniques with much better statistics.

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[*] On leave from the Central Research Inst. for Physics, Budapest, Hungary. Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824.

[†] Present address: Physics Department, State University of New York at Stony Brook, NY 11794.

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