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Flow of nuclear matter in ^{208}Pb -emulsion interactions at 160A GeV

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Abstract

By using the transverse momentum technique, we investigated the nuclear collective flow from the projectile fragments of charge $Z \geq 2$ produced in the interactions of a ^{208}Pb beam at 160A GeV in nuclear emulsion. Flow is observed in a ^{208}Pb beam at 160A GeV and these results are compared with a ^{197}Au beam at 10.6A GeV.

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Heavy ion interactions at relativistic energies produce conditions of extreme pressure and temperature, and thus provide the dynamical conditions needed to study the properties of highly excited and compressed nuclear matter. The main interest in such studies is to search for the existence of a phase transition from normal matter to a quark-gluon plasma (QGP), a deconfined phase of matter. In pursuit of evidence of the formation of a QGP, one has to question whether the matter produced in such collisions can be considered to be in thermal equilibrium locally, which implies that the matter behaves collectively and therefore may have a few observables for its measurement. In nuclear collisions, a part of the compressional energy which reappears in the form of collective flow is strongly influenced by geometrical factors (nucleus and target sizes, impact parameter etc.). For peripheral collisions, where the presence of the reaction plane can be determined from the projectile fragments (PFs), the commonly used method for the determination of collective (directive) flow has been the transverse momentum transfer between target and projectile regions [1]. For central collisions, the reaction plane

disappears and the new form of collective flow, i.e., radial (isotropic) flow from the expansion of the system is observed [2], which plays a critical role in the large fragment multiplicities observed. All fragments do not contribute equally in the collective (radial) expansion. Recently, we applied the method of directed flow [3] to projectile fragments (PFs) of charge $Z \geq 2$ in nuclear emulsion and were quite successful with the ^{197}Au beam at 10.6A GeV from the Alternating Gradient Synchrotron at Brookhaven National Laboratory. We are extending this technique to the PFs of the ^{208}Pb beam at 160A GeV at the CERN Super Proton Synchrotron (SPS) and also compare the flow results of both these beams *for the first time* in this letter.

The data sample used in this paper consists of nuclear interactions in emulsion exposed to the CERN SPS ^{208}Pb beam at 160A GeV (Experiment No. EMU11). The details of the ^{197}Au beam (Expt. No. 875) were given earlier in Ref. [3]. By following along-the-primary tracks of the ^{208}Pb beam, we observed 1034 nuclear events in emulsion (which has the best spatial resolution). The angles of all the PFs were measured with an error of less than 0.1 mrad by the relative primary method [4]. Spectator projectile protons from the projectile nucleus are produced mostly within a very narrow forward cone with semivertex angle $\theta_c \approx 1.3$ mrad, given by the Fermi momentum. The charges of all the PFs were determined by the combination of several methods: grain, gap and δ -ray densities and track widths, as discussed in Ref. [3]. Fig. 1 of Ref. [5] shows the frequency distribution of δ -ray/100 μm for the PFs of charges $3 \leq Z \leq 20$. For the δ -ray density more than 200 δ -rays were counted for each track. A

well-defined peak corresponding to each charge between $3 \leq Z \leq 20$ is observed in Fig. 1 of Ref. [5]. For α -particle identity, grain density ($4g_0$) was used, where g_0 is the minimum ionization in the emulsion. The PFs of higher charges $21 \leq Z \leq 82$ were determined by the track width technique and are not shown here. The charge resolutions obtained for the charges with $Z = 3-4$, $5-12$, $13-20$ and $21-40$ and > 40 are ± 0.4 charge units (cu), ± 0.5 cu, ± 1.0 cu, ± 2.0 cu and 3.0 cu, respectively. Further details on charge determination can be found in Ref. [3].

For the present analysis, we selected events from both beams (^{208}Pb and ^{197}Au) which have at least four PFs (N_{PF}), where the individual charge of the PFs lies in the range of $2 \leq Z \leq 20$. These restrictions reduced the sample of the ^{208}Pb beam to 337 events and that of the ^{197}Au beam to 525 events, where the charge of each PF was determined as discussed above. We have previously shown [3,4] that there is a monotonic relationship between the number of the projectile (spectator) proton, N_p , and the impact parameter (b), with the result that N_p represents the centrality or different temperatures produced at the collision. The proton number, $N_p = Z_{beam} - Z_{bound}$, where Z_{beam} is the primary beam charge and Z_{bound} is the summed charges of all the PFs of $Z \geq 2$ emitted in an event. We have explained earlier [3] that due to bounce-off effects experienced by α -particles, their transverse momenta (P_t) per nucleon distribution has a tail. In Fig. 1, we display the transverse momentum per nucleon of PFs from the ^{208}Pb beam of charges $Z = 2$ and $Z \geq 3$, with respect to the beam direction, with peak values ≈ 120 MeV/c and ≈ 80 MeV/c, respectively. P_t/A values for $Z = 2$ particles go up to 600 MeV/c. As the projectile energy of PFs from the ^{208}Pb beam is much higher than from the ^{197}Au beam, their production angles are much smaller and hence would yield much less bounce-off than at 10.6 A GeV.

At high energies, we assume that the longitudinal momentum per nucleon P_l of the PF is the same as that of the incident projectile P_{pr} of the mass A_{pr} , i.e. $P_l = P_{pr}/A_{pr}$. The transverse momentum per nucleon of the j th fragment $|P_{tj}| = \tan \theta_j |P_l|$, where θ_j is the emission angle of the j th projectile fragment with respect to the primary beam. In the transverse momentum analysis [1], the reaction plane of each single PF is constructed by individually from the transverse momentum component P_t per nucleon of all the remaining PFs of the same event and is given by $Q_i = \sum_{j \neq i} w_j A_j P_{tj}$, where

$w_j = 1$ for the fragments in the forward direction; the sum runs over all particles of the event except for the particle i . In this analysis, autocorrelation has been removed by calculating Q individually for each particle, where Q is only an estimate for the true reaction plane. The transverse momentum vector P_{tj} per nucleon is projected onto the approximate reaction plane by evaluating the scalar product $P_t^x/A = P_{tj} \cdot Q_j / |Q_j|$. In the emulsion technique, we pursue only the forward moving particles; the process of determining the reaction planes by making accurate measurements of the charge and the small forward angle of relativistic PFs is unique to this technique. The more commonly electronic experiments are not sensitive at sufficiently small angles.

Fig. 2(a) shows the average transverse momentum transfer per nucleon of PFs with $Z \geq 2$ projected into the reaction plane $\langle P_t^x/A \rangle$ against P_t/A for the ^{208}Pb as well as for the ^{197}Au beams for comparison. The bounce-off of the PFs is generally recognized by the pronounced peak structure of the transverse momentum transfer. The errors shown are all statistical. For the ^{197}Au beam the bounce-off [3] is quite visible in Fig. 2(a) via a pronounced peak value of the $\langle P_t^x/A \rangle$ distribution function around 205 MeV/c at the P_t/A value of ≈ 450 MeV/c. The peak value of $\langle P_t^x/A \rangle$ observed in ^{197}Au beam is more than a factor of two of that observed in Ref. [6]. In the case of the ^{208}Pb beam, for small values of P_t/A , the distribution of $\langle P_t^x/A \rangle$ goes on increasing almost linearly and after the value of $P_t/A \approx 450$ MeV/c, the functional value of $\langle P_t^x/A \rangle$ is saturated at ≈ 350 MeV/c. The saturation value for the ^{208}Pb beam is higher than for the ^{197}Au beam which occurs almost at the same value of $P_t/A \approx 450$ MeV/c. In Fig. 2(b), we separated α events from both the beams and find that the distributions for events with $Z \geq 3$ are almost similar to the ones shown in Fig. 2(a). In the ^{208}Pb beam no pronounced peak is observed and this is different from the observations of the ^{197}Au beam, where the peak is quite visible. For no flow case, $\langle P_t^x/A \rangle$ distribution instead of showing either a peak or a saturation, would show a continuous linear relation which is not the case here with either lead or gold beam. In both beams the $\langle P_t^x/A \rangle$ values increase with heavier PFs of $Z \geq 3$ [7] and they are larger for the ^{208}Pb when compared to the ^{197}Au beam and this is exhibited in Fig. 2(b). The cut off values of P_t/A in both of the beams in Fig. 2 are justified from Fig. 1 for the ^{208}Pb beam and from Fig. 1(b) of Ref. [3] for the ^{197}Au beam, as

the beam energy of the ^{208}Pb beam is quite high, the emitted angles of their PFs are much smaller as compared to the ^{197}Au beam. Thus, we can say that when we apply the same technique to the PFs of both the ^{197}Au and the ^{208}Pb beams, we find that our results are consistent with lower particle stopping in the ^{208}Pb beam at CERN energy compared to that in the ^{197}Au beam at the AGS energy. Furthermore, the evidence for directed flow is also observed in the azimuthal correlation function of PFs of both beams [8]. These functions are not sensitive to the direction of the collective flow but are sensitive to their magnitudes. In that work [8] we find that the strength of the correlation function for the ^{208}Pb beam is much larger when compared with the corresponding values of the ^{197}Au data. It was also reported that in the ^{197}Au beam stopping approaches 100% in central $^{197}\text{Au} + ^{197}\text{Au}$ collisions [6], while the relative stopping in $^{208}\text{Pb} + ^{208}\text{Pb}$ at the CERN SPS is only $57 \pm 6\%$ [9]. The stopping in the ^{208}Pb beam is still very high as compared to $^{32}\text{S} + ^{32}\text{S}$ at the SPS and there is no indication of significant nuclear transparency in collisions with the ^{208}Pb beam.

In order to be sure that the reaction planes for the ^{208}Pb beam were determined accurately, we subdivided each event randomly into two subevents and subsequently evaluated the correlation of the two. The difference between the azimuthal angles ($\Delta\phi$) of the two estimated planes is shown in Fig. 2(c). They all peak near zero (side-by-side) indicating that the reaction planes are real and they have a real physical correlation among the particles. The accuracy of the true reaction plane is $\sigma_0 \approx 20^\circ$ and this value is comparable to the accuracy reported for other techniques used. The analysis of the reaction planes further supports the idea that there is stopping which generates flow. If there was no flow at all, there would have been no reaction plane, and hence no correlation between the azimuthal angles ($\Delta\phi$) would have existed and this is contrary to our observations in the ^{208}Pb beam interactions as seen in Fig. 2(c).

If we study the correlation in position space rather than in momentum space of the PFs produced in nuclear reactions, then the distribution of the fraction of the transverse momentum of these PFs is shown in Fig. 2(d), where $\langle P_t^x/P_t \rangle$ is plotted against pseudorapidity η_{lab} for the ^{208}Pb beam as well as for the ^{197}Au beam. At this energy, backward moving particles are not shown and the shape of the distribution show flow, consistent with the observa-

tions seen in Figs. 2(a) and 2(b). The peaks in both beams are occurring near the respective values of their beam pseudorapidity (i.e., $\eta_{lab} \approx 5$ and 7). The mean values of the in-plane transverse momentum near the projectile pseudorapidity of the ^{208}Pb beam is higher as compared to the ^{197}Au beam and they both exhibit flow as depicted in Fig. 2(d).

The normalized azimuthal angle distributions of $Z \geq 2$ fragments with respect to the reaction plane are displayed in Figs. 3(a) and 3(b) for the ^{208}Pb and ^{197}Au beams, respectively. In these figures, we performed a second order Legendre polynomial fit, $N(\phi) = 1 + P_1 \cos \phi + P_2 \cos 2\phi$, through the azimuthal angle distributions [10] and such a fit is represented by a solid line. The single hump structure is quite visible in both Figs. 3(a) and 3(b). This indicates the dominance of the side-splash of particles into the target and projectile hemispheres. The fitting of the polynomial for the ^{208}Pb beam in Fig. 3(a) gives values of $P_1 = -0.076 \pm 0.013$ and $P_2 = 0.849 \pm 0.017$ with $\chi^2 = 3.3$, while for the ^{197}Au beam in Fig. 3(b) $P_1 = 0.078 \pm 0.017$ and $P_2 = 0.226 \pm 0.023$ with $\chi^2 = 3.0$. In both cases, $R < 1$. The parameter P_1 is sensitive to directed sideward flow and its magnitude is almost equal for both beams. It is a measure of forward-backward asymmetry and determines the strength of the in-plane flow. The negative sign of P_1 indicates preferential emission of PFs pairs to the opposite side of the beam. P_2 is related to the ratio of out-of-plane to in-plane intensity (anisotropy) and if negative it measures the particle emission perpendicular to the reaction plane: the so-called "squeeze-out" effect [10]. The positive value of P_2 indicates rotational behavior and no squeeze-out effect. The rotational collective motion for the ^{208}Pb beam is much higher than for the ^{197}Au beam. The squeeze-out ratio R is defined as $R = [N(90^\circ) + N(270^\circ)]/[N(0^\circ) + N(180^\circ)] = (1 - P_2)/(1 + P_2)$. The value $R > 1$ implies preferred out-of plane emission with a single hump structure in Fig. 3. There is no squeeze-out effects on the PFs with $Z \geq 2$ and hence no large "nuclear transparency" in the system.

We conclude that for the first time the collective flow determined by the method of PFs of charge $Z \geq 2$ produced in the ^{208}Pb -emulsion interactions at 160A GeV is quite significant when compared with the ^{197}Au beam at 10.6A GeV. In both the beams, the flow increases with the increase in the charge of the projectile fragments.

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Figure Captions

Fig. 1 Transverse momentum per nucleon P_t/A distribution for the events with $N_{PF} \geq 4$ of charge $Z = 2$ (solid histogram) and $Z \geq 3$ (dashed histogram) for the ^{208}Pb data at 160A GeV.

Fig. 2 (a) Variation of $\langle P_t^x/A \rangle$ with P_t/A projected into the reaction plane for the PFs of charges $Z \geq 2$ for the ^{208}Pb (filled circles) and ^{197}Au (filled triangles) beams. (b) The same as in Fig. 2(a), but for the PFs with $Z = 2$ and $Z \geq 3$. Open ($Z \geq 3$) and closed ($Z = 2$) circles are for the ^{208}Pb data, whereas open ($Z \geq 3$) and closed ($Z = 2$) triangles are for the ^{197}Au data. For clarity the data points for

$Z \geq 3$ are slightly shifted along the x-direction. Dotted lines in Figs. 2(a) and (b) are drawn to guide the eye. (c) Distribution of difference of azimuthal angles $\Delta\phi$ for the vectors Q_1 and Q_2 constructed from two halves of every event with $N_{PF} \geq 4$ of $Z \geq 2$ for the ^{208}Pb data. (d) $\langle P_t^x/P_t \rangle$ as a function of η_{lab} for ^{208}Pb (filled circles) and ^{197}Au (filled triangles) data with $Z \geq 2$. Solid line is a polynomial fit through the data points of ^{208}Pb beam, while a dotted line is that for the ^{197}Au data.

Fig. 3 The normalized azimuthal angle ($\Delta\phi$) distributions obtained in the reaction plane for the projectile fragments of charges of charge $Z > 2$ for the: (a) ^{208}Pb data at 160A GeV and (b) ^{197}Au data at 10.6A GeV. Solid lines in Figs. 3(a) and 3(b) are the Legendre fits as explained in text. Symbols used here are those as given in Fig. 3(d).