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Onset of flow of charged fragments in Au-Au collisions

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The reaction plane of high-multiplicity Au-Au collisions at 650, 400, 250, 150, and 75 MeV/nucleon was determined by measuring the transverse velocity of charged fragments. Measurements of the collective flow of charged fragments reveal that the onset of flow in high-multiplicity Au-Au collisions occurs at a finite beam energy below 60 MeV/nucleon.

Collective flow of nuclear matter in relativistic heavy-ion collisions was predicted on the basis of hydrodynamics,[1-3] and was observed unambiguously by experiments with 4π detectors (viz., the Plastic Ball[4-7] and the streamer chamber[8-12]). Quantitative measurements of collective flow have endeavored to set constraints on properties such as the incompressibility modulus of the equation of state of nuclear matter.[13] Molitoris and Stöcker[14] and Bertsch, Lynch, and Tsang[15] discussed the fact that the mean-field interaction changes from repulsive to attractive as the bombarding energy decreases. This transition energy represents the onset of collective flow from the repulsive interaction. Krofcheck *et al.*[16] reported the disappearance of collective flow in La-La collisions at 30–50 MeV/nucleon. In this Rapid Communication, we report the first observation of the onset of collective flow in collisions of two very heavy (viz., ^{197}Au) nuclei. Also, this determination of the onset energy is the first one that takes into account the dispersion of the determined reaction plane in nucleus-nucleus collisions.

Previously, the sphericity method[17,18] and the global transverse momentum method[19] were used to analyze measurements of collective flow of charged fragments. Gyulassy[20] proposed a transverse velocity method, which is an adaptation of the global transverse momentum method, to determine the azimuthal angle ϕ_R of the reaction plane without the need for particle identification.

In this experiment, we determined the reaction plane of high-multiplicity Au-Au collisions at 650, 400, 250, 150, and 75 MeV/nucleon by measuring the transverse velocity of charged fragments. The average in-plane transverse velocity of charged fragments reflects collective flow. Also, we measured the momentum distribution of neutrons emitted from these collisions and their azimuthal distribution relative to the determined reaction plane. The findings for neutrons will be presented in a later report.

The experiment was carried out at the Bevalac accelerator at the Lawrence Berkeley Laboratory. Projectile ions traversed a beam telescope before interacting with the target. A plastic wall array, 5 m wide and 4.5 m high, with 184 scintillation detectors was used to detect charged fragments emitted from each interaction. The flight paths to the 184 detectors ranged from 4.0 to 5.0 m. The velocity of the charged fragments detected in the plastic wall in each collision was extracted from the measured time of flight. The multiplicity of the detected charged fragments indicated the degree of centrality of the collision. The uncertainty in the velocity was typically 7% for 650-MeV/nucleon charged fragments detected in the plastic wall; about half of the uncertainty came from the intrinsic time dispersion of the detectors, and the other half from the uncertainty in the position of the charged fragments. Thin steel sheets, which covered the front side of the 24 inner detectors, were used to absorb the δ rays produced as the beam traversed the air. The thicknesses of the steel were 1.37, 0.91, 0.46, and 0.46 mm, respectively, for 650, 400, 250, and 150 MeV/nucleon. From the coincidence rate in pairs of neighboring detectors, the double-hit rate of charged particles was estimated to be $(20\pm5)\%$ for Au-Au collisions at 650 MeV/nucleon. The loss of information from these relatively small double-hit rates does not have a significant effect on the determination of the reaction plane. For the bombarding energies of 650, 400, 250, 150, and 75 MeV/nucleon, target thicknesses were 1.7, 1.7, 1.1, 0.59, and 0.26 g/cm^2, and the resulting energy spreads were ±37, ±44, ±37, ±25, and ±17 MeV/nucleon, respectively. We selected collisions with a charged multiplicity $M > M_0 = 35$, 33, 31, 29, and 24 for Au beam energies of 650, 400, 250, 150, and 75 MeV/nucleon beam, respectively. With the target removed, measurements of the multiplicity distribution showed that less than 5% of these selected high-multiplicity collisions could be attributed to the background contamination from collisions of Au with the air or the material in the beam telescope. The events selected with the cutoff multiplicity M_0 roughly corresponded to the most central 9% of the total geometric cross section for the highest four energies and 4% for 75 MeV/nucleon. In estimating these percentages of the total geometric cross section, the total number of events detected was corrected for the detection efficiency of each event, which is approximately proportional to its multiplicity M.

The azimuthal angle ϕ_R of the reaction plane was estimated from the vector $\mathbf{Q}$, the weighted sum of the transverse velocity vectors of all charged fragments detected in each collision:

$$\mathbf{Q}=\sum_{i=1}^{M}\omega_i \mathbf{V}_i^t,\quad \omega_i=\begin{cases}1/V_i^t & \text{for } \alpha\geq\alpha_0\\ 0 & \text{for } \alpha<\alpha_0,\end{cases} \tag{1}$$

where the quantity $\alpha\equiv(Y/Y_P)_{\text{c.m.}}$ is the rapidity normalized to the projectile rapidity in the center of mass, ω_i is a weighting factor, and α_0 is a rapidity threshold. The weighting factor ω_i was chosen to minimize the dispersion $\Delta\phi_R$.[20] Because the weighted transverse velocity vector for the ith fragment ($\omega\mathbf{V}_i^t=\mathbf{V}_i^t/V_i^t$) is a unit vector which depends only on the azimuthal position of the detector struck by the fragment, a possible systematic uncertainty in the time calibration of the detectors in the plastic wall was avoided in the calculation of the unit velocity vector $\mathbf{V}_i^t/V_i^t$.

To estimate the dispersion $\Delta\phi_R$, we adapted the global transverse momentum method of Danielewicz and Odyniec[19] to our experiment. First, we determined the weighted in-plane transverse velocity of each charged fragment, projected on the reaction plane estimated by the vector $\mathbf{Q}_i'$, determined now by excluding the considered charged particle to remove autocorrelations,

$$(\omega_i V_i^x)'=(\omega_i\mathbf{V}_i^t)\cdot\mathbf{Q}_i'/Q_i',\quad \mathbf{Q}_i'=\sum_{j\neq i}^{M}\omega_j\mathbf{V}_j^t\,. \tag{2}$$

Then, we calculated the average $\overline{(\omega V^x)'}$ of the weighted in-plane transverse velocity of the charged fragments in all events above the rapidity threshold α_0; the same average, projected on the "true" reaction plane, was obtained from the following formula:

$$\overline{\omega V^x}=\left[\frac{\overline{Q^2-\sum(\omega_i V_i^t)^2}}{\overline{N(N-1)}}\right]^{1/2}=\left[\frac{\overline{Q^2-N}}{\overline{N(N-1)}}\right]^{1/2}, \tag{3}$$

where N $[\equiv M(\alpha\geq\alpha_0)]$ is the number of charged fragments above the rapidity threshold α_0, and the averages in both the numerator and the denominator are over all events. For small values of $\Delta\phi_R$, the cosine of $\Delta\phi_R$ is equal approximately to the ratio of the two averages[19,20]

$$\cos(\Delta\phi_R)\approx\frac{\overline{(\omega V^x)'}}{\overline{\omega V^x}}\,. \tag{4}$$

Plotted in Fig. 1 are the dispersions $\Delta\phi_R(\geq\alpha)$ versus the rapidity threshold α_0 for high-multiplicity Au-Au collisions from 150 to 650 MeV/nucleon. The minima of the dispersions $\Delta\phi_R$, which occur at α_0 values between 0.2 and 0.4, range from about 25° for 650 MeV/nucleon to about 40° for 150 MeV/nucleon. At 75 MeV/nucleon, the ratio of $\overline{(\omega V^x)'}$ to $\overline{\omega V^x}$ is only 0.34 at $\alpha_0=0.3$, which is too small to extract a reliable value for the dispersion $\Delta\phi_R$. The uncertainties in the dispersion $\Delta\phi_R$ in Fig. 1 are dominated by the systematic uncertainties, which come from uncertainties in the rapidity and the direction of the charged fragments. This uncertainty of about 5% propagates to dispersion uncertainties shown in Fig. 1 of typically 10%.

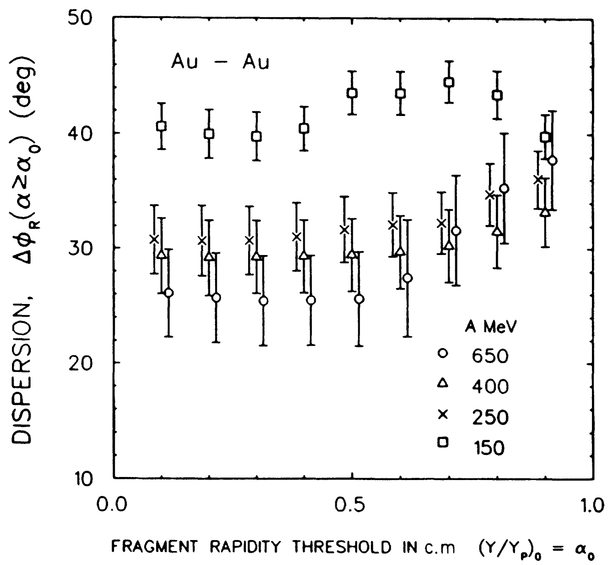

FIG. 1. Dispersion $\Delta\phi_R(\alpha\geq\alpha_0)$ for charged fragments detected above a normalized rapidity α_0 vs the fragment rapidity. For clarity, the points at 250 and 650 MeV/nucleon are displaced slightly from the α_0 values at 400 MeV/nucleon.

The average-weighted in-plane transverse velocity $\overline{\omega V^x}=\overline{V^x/V^t}$, which was used to determine the dispersion $\Delta\phi_R$, reflects the collective flow of charged fragments. Plotted in Fig. 2 as a function of beam energy are $\overline{V^x/V^t}$, the average normalized in-plane transverse velocity projected on the "true" reaction plane, and $\overline{(V^x/V^t)'}$, the average normalized in-plane transverse velocity projected on the "estimated" reaction plane. The average is over all charged fragments with $\alpha\geq\alpha_0=0.3$. In Fig. 2, the vertical error bars show the dominating systematic uncertain-

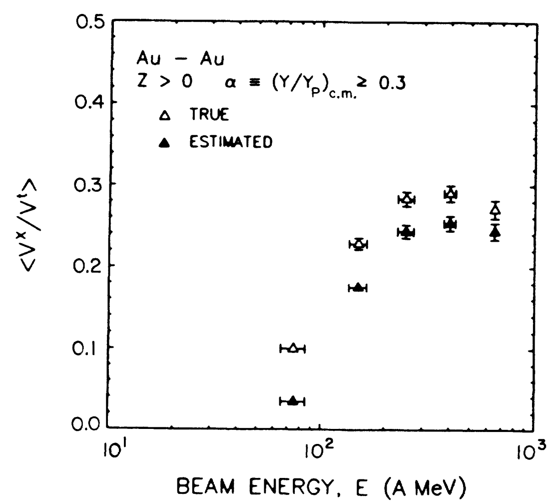

FIG. 2. Average normalized in-plane transverse velocities $\overline{(V^x/V^t)'}$ and $\overline{(V^x/V^t)}$ projected, respectively, on the estimated and "true" reaction planes as a function of bombarding energy for Au-Au collisions.

ties arising from the determination of the rapidity and the direction of the charged fragment, and each horizontal error bar reflects the spread in the projectile energy from the uncertainty in the interaction point in the target. The average values of $\overline{V^x/V^t}$ for 150- and 250-MeV/nucleon Au-Au collisions can be compared to the normalized average in-plane transverse momenta at the projectile rapidities for the 200-MeV/nucleon Au-Au results from the Plastic Ball[7] because P^x/P^t is equal to V^x/V^t. The values of $\overline{V^x/V^t}$ determined in this experiment are 0.23 and 0.28 for 150 and 250 MeV/nucleon, respectively. The Plastic Ball value of $\overline{P^x/P^t}$ shown in Fig. 3 of Ref. 7 is about 0.2 for $Z=1$ and increases to about 0.5 for $Z\geq 6$. Because this experiment did not distinguish between different charges, our values represent an average over all charges. These values are close to the Plastic Ball values for fragments with low Z, which have larger cross sections than those with higher Z. A proper comparison of our data with the Plastic Ball results in Fig. 3 of Ref. 7 should take into account differences in multiplicity bins. Although the multiplicities for our data at 150 and 250 MeV/nucleon match approximately their fourth multiplicity bin,[7] and although the Plastic Ball data in Fig. 3 of Ref. 7 are presented for their third multiplicity bin, the difference in the collective flow for these two multiplicity bins is only about 10%.[6] When the acceptances of the Plastic Ball detector system are folded into model calculations (e.g., Vlasov-Uehling-Uhlenbeck) with the Plastic Ball filter program,[5,21] the magnitude of the in-plane transverse momentum at projectile rapidities increases substantially (e.g., by several tens of percent); however, because the ratio V^x/V^t $(=P^x/P^t)$ depends on angle only, this ratio is much less sensitive to differences in the acceptances between the two detector systems.

The major objective of reducing the beam energy was to look for the onset of flow in Au-Au collisions. For this purpose, we investigated the average absolute in-plane transverse velocities $\overline{(V^x/c)}'$ and $\overline{V^x/c}$ projected on the estimated and "true" planes, respectively, by changing the weighting factor ω_i in Eqs. (1)–(3) from $1/V_i^t$ to $1/c$. The average in-plane transverse velocities $\overline{(V^x/c)}'$ and $\overline{V^x/c}$ depend on the direction and the velocity of each charged fragment. Plotted in Fig. 3 are the two average in-plane transverse velocities $\overline{(V^x/c)}'$ and $\overline{V^x/c}$ as a function of the bombarding energy for Au-Au collisions. The error bars in Fig. 3 reflect the same uncertainties as those in Fig. 2. We chose to present these data as a function of the logarithm of the bombarding energy because the average velocity $\overline{V^x/c}$ shows a linear dependence on the logarithm of the beam energy E for the four points in the energy region from 75 to 400 MeV/nucleon. We extrapolated this logarithmic dependence in Fig. 3 to energies below 75 MeV/nucleon. The solid line shown in Fig. 3 displays the extrapolation. The intersection of the solid line with the abscissa is 47 ± 11 MeV/nucleon. The uncertainty in the intersection arises from the uncertainty in the interaction energy of the collision between the projectile and the target, which is much larger than the statistical and other systematic uncertainties.

We examined the sensitivity of the intersection energy to the form of the fitting function and the energy region of

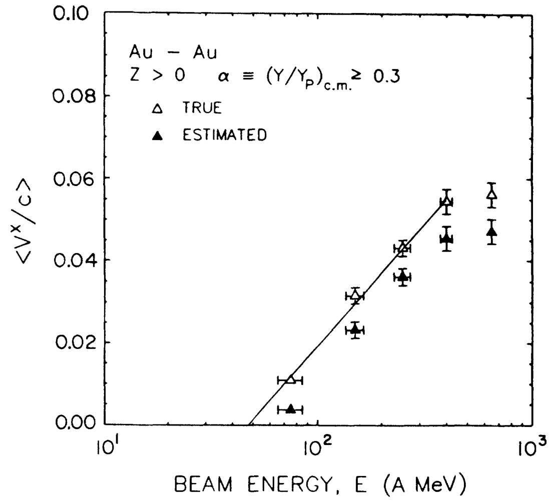

FIG. 3. Average in-plane transverse velocities $\overline{(V^x/c)}'$ and $\overline{V^x/c}$ projected, respectively, on the estimated and "true" reaction planes as a function of bombarding energy for Au-Au collisions. The solid line shows a fit to the data of $\overline{(V^x/c)}$ at energies between 75 and 400 MeV/nucleon and its extrapolation to energies below 75 MeV/nucleon.

the data points used in the extrapolation. We found that a second-order polynomial function yields a reasonable fit to the three data points in the energy region from 75 to 250 MeV/nucleon, and that a linear function does not yield a reasonable fit if it includes more than the two data points at 75 and 150 MeV/nucleon. The results listed in the upper three rows of Table I show that the absolute uncertainty decreases as the number of data points increases, and that the intersection energy is insensitive to the choice of the fitting functions. When the same extrapolations are applied to the normalized average in-plane transverse velocity $\overline{V^x/V^t}$ shown in Fig. 2, the intersection energies E_0 listed in the bottom three rows of Table I cannot be distinguished within uncertainties from those obtained by extrapolating $\overline{V^x/c}$; however, the mean values of the intersection energy obtained by extrapolating $\overline{V^x/V^t}$ are systematically lower than those that were obtained by extrapolating $\overline{V^x/c}$. It is easy to show that the linear extrapolation of $\overline{V^x/V^t}$ yields a systematically lower intersection energy than the linear extrapolation of $\overline{V^x/c}$; this result is based only on the fact that V^t for the lower energy point is smaller than V^t for the upper energy point. The linear extrapolation of $\overline{V^x/V^t}$ shows an intersection energy of nearly one standard deviation away from zero. Relatively large uncertainties in the intersection energy are inevitable for the linear extrapolation with only two data points. The results summarized in Table I indicate an onset of flow at a finite beam energy below 60 MeV/nucleon for central collisions of two gold nuclei.

The data at 75 MeV/nucleon were extracted from collisions that are more central than those at the other energies. The values of $\overline{V^x/V^t}$ and $\overline{V^x/c}$ at 75 MeV/nucleon shown in Figs. 2 and 3 should be corrected for the difference in the degree of centrality in order to make a proper extrapolation. From our data at 150 MeV/nucleon, the values of $\overline{V^x/V^t}$ and $\overline{V^x/c}$ for central col-

TABLE I. Summary of extrapolations of the average absolute transverse velocity $\overline{V^x/c}$ and the normalized average transverse velocity $\overline{(V^x/V^t)}$ in true reaction plane.

	Extrapolation function[a]	Region of beam energy E (MeV/nucleon)	Intersection E_0 (MeV/nucleon)
	$C_0+C_1 \ln E$	75–400	47 ± 11
$\overline{V^x/c}$	$C_0+C_1E+C_2E^2$	75–250	43 ± 14
	C_0+C_1E	75–150	36 ± 16
	$C_0+C_1 \ln E$	75–250	41 ± 8
$\overline{V^x/V^t}$	$C_0+C_1E+C_2E^2$	75–250	27 ± 9
	C_0+C_1E	75–150	16 ± 20

[a]C_0, C_1, and C_3 are constants.

lisions that correspond to 4% of the total geometric cross section are about 8% and 4%, respectively, larger than those used in Table I. We increased the values of $\overline{V^x/V^t}$ and $\overline{V^x/c}$ at 75 MeV/nucleon by 8% and 4%, respectively, and repeated all extrapolations; the resulting intersection energies are the same within uncertainties as those shown in Table I.

The intersection points are higher than those shown in Table I for the data projected on the estimated reaction plane. Krofcheck *et al.*[16] overestimated the onset energy because the multiplicities in La-La collisions were too low to enable a reliable determination of the "true" reaction plane.

In this experiment, a logarithmic fit of $\overline{V^x/c}$ to four data points indicates that this collective flow signature for charged fragments in Au-Au collisions vanishes at a bombarding energy of 47 ± 11 MeV/nucleon; furthermore, fits with other functions are consistent with this finite energy for the onset of collective flow. This measurement has potential for providing a new constraint on properties of the nuclear equation of state.

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