Azimuthal Anisotropy at the Relativistic Heavy Ion Collider: The First and Fourth Harmonics

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We report the first observations of the first harmonic (directed flow, v_1) and the fourth harmonic (v_4), in the azimuthal distribution of particles with respect to the reaction plane in Au + Au collisions at the BNL Relativistic Heavy Ion Collider (RHIC). Both measurements were done taking advantage of the large elliptic flow (v_2) generated at RHIC. From the correlation of v_2 with v_1 it is determined that v_2 is positive, or *in-plane*. The integrated v_4 is about a factor of 10 smaller than v_2. For the sixth (v_6) and eighth (v_8) harmonics upper limits on the magnitudes are reported.

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Anisotropic flow, an anisotropy of the particle azimuthal distribution in momentum space with respect to the reaction plane, is a sensitive tool in the quest for the quark-gluon plasma and the understanding of bulk properties of the system created in ultrarelativistic nuclear collisions [1]. It is commonly studied by measuring the Fourier harmonics (v_n) of this distribution [2]. Elliptic flow, v_2, is well studied at RHIC [3–5] and is thought to reflect conditions from the early time of the collision. Directed flow, v_1, was discovered almost 20 years ago [6] and has been extensively studied and reviewed at lower beam energies [7]. At RHIC energies directed flow in the central rapidity region reflects important features of the system evolution from its initial conditions. v_1 is predicted to be small near midrapidity with almost no dependence on pseudorapidity. However, it could exhibit a characteristic "wiggle" [8], depending on the baryon stopping and production mechanisms as well as strong space-momentum correlations in the system's evolution. A similar rapidity dependence of directed flow could develop due to a change in the matter compressibility if a quark-gluon plasma is formed [9,10]. It results in the so-called third flow component [9] or "antiflow" [10] component in the expansion of the matter. This expansion direction is opposite the normal directed flow. v_1 has not previously been reported at RHIC.

The importance of the higher harmonics in understanding the initial configuration and the system evolution has been emphasized [11]. Recently, Kolb [12] reported that the magnitude and even the sign of v_4 are more sensitive than v_2 to initial conditions in the hydrodynamic calculations. Those higher harmonics reflect the details of the initial configuration geometry. Besides one early measurement at the Alternating Gradient Synchrotron [13], reports of higher harmonics have not previously been published.

Experiment.—The data come from the reaction Au + Au at $\sqrt{s_{NN}} = 200$ GeV. The STAR detector [14] main time projection chamber (TPC [15]) and two forward TPCs (FTPC [16]) were used in the analysis. For the higher harmonics 2×10^6 events in the main TPC were analyzed. For the first harmonic analysis there were 70 000 events available which included the FTPCs.

In this analysis the main TPC covered pseudorapidity (η) from -1.2 to 1.2, while two FTPCs covered -4.2 to -2.4 and 2.4 to 4.2. The low transverse momentum (p_t) cutoff was 0.15 GeV$/c$. In the present work all charged particles were analyzed, regardless of their particle type. The centrality definition in this Letter is the same as used previously by STAR [17]. The errors presented in the figures are statistical.

Analysis.—The difficulties in studying directed flow are that the signal is small and the nonflow contribution to the two-particle azimuthal correlations can be comparable to or even larger than the correlations due to flow. To suppress the nonflow effects, the current analysis uses the knowledge about the reaction plane derived from the large elliptic flow. One method for eliminating the nonflow contribution in a case when the reaction plane is known was proposed in [2]. It was noted that while the correlations of the components of the (first harmonic) flow vectors in the reaction plane contain both flow and nonflow contributions, the correlations of the components perpendicular to the reaction plane contain only nonflow contributions. Then the difference yields the flow contribution. Correlating the azimuthal angles of two particles (ϕ_a, ϕ_b), and using the event plane determined by elliptic flow (Ψ_2) one gets

$$\langle\cos(\phi_a - \Psi_2)\cos(\phi_b - \Psi_2) - \sin(\phi_a - \Psi_2)\sin(\phi_b - \Psi_2)\rangle = \langle\cos(\phi_a + \phi_b - 2\Psi_2)\rangle \approx v_{1,a}v_{1,b}\langle\cos(2(\Psi_2 - \Psi_{RP}))\rangle, \tag{1}$$

where Ψ_{RP} is the azimuthal angle of the reaction plane. If only one particle is used to determine the second harmonic event plane, this expression reduces to

$$\langle\cos(\phi_a + \phi_b - 2\phi_c)\rangle \approx v_{1,a}v_{1,b}v_{2,c}, \tag{2}$$

which is the basic formula of the three-particle correlation method of Borghini, Dinh, and Ollitrault [18]. The analysis of directed flow in this Letter is performed using this three-particle cumulant method [18]. The analyses for v_4, v_6, and v_8 were done relative to the second harmonic event plane using the method described in Refs. [2,19], with the event plane resolution calculated from Eq. (11) of Ref. [2] with $k = 2$, 3, or 4. Note that this approach in many aspects is very similar to the analysis of directed flow described above as it also involves three (for v_4, and four for v_6) particle correlations. For example, for the fourth harmonic flow (approximately, for the exact relations actually used in the analysis, see [2]),

$$\langle\cos(4\phi - 4\Psi_2)\rangle \approx v_2^2 v_4 N/2, \tag{3}$$

where N is the total number of particles used to determine the second harmonic event plane. This expression should be compared to Eq. (2). Results obtained with this method we designate by $v_4\{EP_2\}$. The analysis for v_4 was also done with three-particle cumulants [20] by measuring $\langle\cos(2\phi_a + 2\phi_b - 4\phi_c)\rangle$.

v_1 *results.*—Figure 1 shows the results in comparison to the lower beam energy data at the Super Proton Synchrotron (SPS) of NA49 [21]. The NA49 data are also replotted so as to be at the same distance from beam rapidity [22] as the STAR results. The RHIC $v_1(\eta)$ results differ greatly from the unshifted SPS data in that they are flat near midrapidity and become significant only at the highest rapidities measured. However, when plotted in the projectile frame relative to their respective beam rapidities, they look similar. It should be noted that, at the SPS energies of 40A and 158A GeV [21], this $y - y_{beam}$ scaling does not work, but y/y_{beam} scaling does. In the pseudorapidity region $|\eta| < 1.2$, $v_1(\eta)$ is approximately flat with a slope of $[-0.25 \pm 0.27(\text{stat})]$% per unit of pseudorapidity, which is consistent with predictions [8–10].

Note that the sign of v_1 is undetermined because v_1 enters as the square in Eq. (2). We have plotted v_1 in the positive hemisphere going negative toward beam rapidity as it does at the lower beam energy. In the NA49 analysis

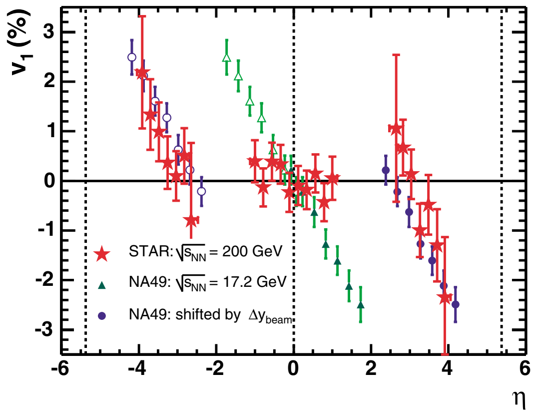

FIG. 1 (color online). The values of v_1 (stars) for charged particles for 10% to 70% centrality plotted as a function of pseudorapidity. Also shown are the results from NA49 (triangles) for pions from 158A GeV Pb + Pb midcentral (12.5% to 33.5%) collisions plotted as a function of rapidity. The open points have been reflected about midrapidity. The NA49 points have also been shifted (circles) plus or minus by the difference in the beam rapidities of the two accelerators. The dashed lines indicate midrapidity and RHIC beam rapidity. Both results are from analyses involving three-particle cumulants, $v_1\{3\}$.

[21] the sign of v_1 had been determined by defining v_1 for protons near beam rapidity to be positive for peripheral collisions. On the other hand, since the measured correlation of Eq. (2) is positive, we can conclude that we have measured the sign of v_2 to be positive. While the absolute values of v_2 at RHIC are well determined [3–5], this is the first direct indication that the elliptic flow at RHIC is *in-plane*.

v_4 results.—The results as a function of p_t are shown in Fig. 2 for minimum bias collisions (0%–80% centrality). Shown for v_4 are both the analysis relative to the second harmonic event plane, $v_4\{EP_2\}$, and the three-particle cumulant, $v_4\{3\}$. Both methods determine the sign of v_4 to be positive. As a function of p_t, v_4 rises more slowly from the origin than v_2, but does flatten out at high p_t like v_2. The $v_6(p_t)$ values are consistent with zero. The hydrodynamic calculations of Kolb [12] for pions from $b = 7$ fm collisions agree very well with our measured v_4 for charged particles for centrality 20% to 30%. However, he calculates v_6 to be -1.2% at 2 GeV/c, while we observe in Fig. 2 for minimum bias data that it is essentially zero. It also appears to be zero in our data for all the individual centralities. Ollitrault has proposed [23] for the higher harmonics that v_n might be proportional to $v_2^{n/2}$ if the ϕ distribution is a smooth, slowly varying function of $\cos(2\phi)$. In order to test the applicability of this scaling, we have also plotted v_2^2 and v_2^3 in the figure as dashed lines. The proportionality constant has been taken to be 1.2 in order to fit the v_4 data.

Kolb [12] points out that for $v_2 > 10\%$, which occurs at high p_t, and no other harmonics, the azimuthal distribution is not elliptic, but becomes "peanut" shaped. He calculates the amount of v_4 (which looks like a four-leaf clover) needed to eliminate this waist. Our values of v_4 as a function of p_t are about a factor of 2 larger than needed to just eliminate this waist.

The results for v_4 as a function of pseudorapidity are approximately flat in the acceptance of the main TPC ($|\eta|<1.2$) with an average value of $(0.44 \pm 0.02)\%$. However, in the FTPCs ($2.7<|\eta|<4.0$) the average value is $(0.06 \pm 0.07)\%$, consistent with zero, with a two sigma upper limit of 0.2%. Consistent with the first observation by PHOBOS [5], at $\eta = 3$ for minimum bias collisions we observe $v_2 = (3.06 \pm 0.10)\%$, which is a factor of 1.8 smaller than at midrapidity. Thus, v_4 seems to fall off faster at high rapidity than v_2. This faster falloff at high pseudorapidity is also consistent with v_4 scaling like v_2^2.

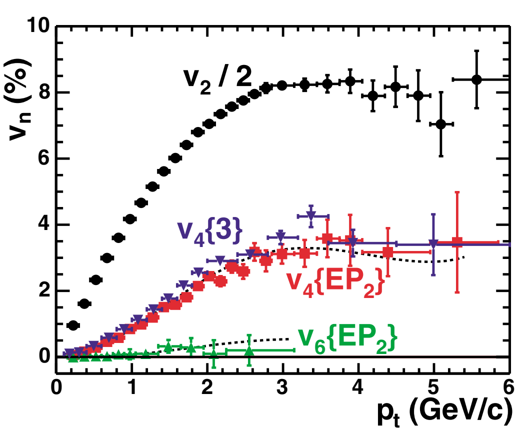

FIG. 2 (color online). The minimum bias values of v_2, v_4, and v_6 with respect to the second harmonic event plane as a function of p_t for $|\eta|<1.2$. The v_2 values have been divided by a factor of 2 to fit on scale. Also shown are the three particle cumulant values (triangles) for v_4 ($v_4\{3\}$). The dashed curves are $1.2v_2^2$ and $1.2v_2^3$.

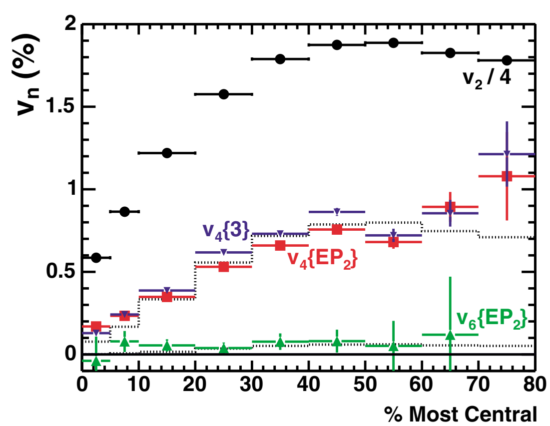

FIG. 3 (color online). The p_t- and η-integrated values of v_2, v_4, and v_6 as a function of centrality. The v_2 values have been divided by a factor of 4 to fit on scale. Also shown are the three particle cumulant values for v_4 ($v_4\{3\}$). The dotted histograms are $1.4v_2^2$ and $1.4v_2^3$.

Figure 3 shows the centrality dependence for p_t-integrated v_2, v_4, and v_6 with respect to the second harmonic event plane and also v_4 from three-particle cumulants ($v_4\{3\}$). The five-particle cumulant, $v_4\{5\}$ (not shown in the figure), is consistent with both methods, but the error bars are about 2 times larger. The v_6 values are close to zero for all centralities. These results are averaged over p_t, thus reflecting mainly the low p_t region where the yield is large, and also averaged over η for the midrapidity region accessible to the STAR TPC ($|\eta|<1.2$). To again test the applicability of $v_2^{n/2}$ scaling we have also plotted v_2^2 and v_2^3 in the figure as dotted histograms. The proportionality constant has been taken to be 1.4 to approximately fit the v_4 data. The larger constant here compared to that used in Fig. 2 is understood as coming from the use of the square of the average instead of the average of the square, and because the integrated values yield-weight low p_t more, where the best factor is slightly larger.

The $v_n\{EP_2\}$ values averaged over p_t and η ($|\eta|<1.2$), and also centrality (minimum bias, 0%–80%), are (in percent) $v_2 = 5.18 \pm 0.005$, $v_4 = 0.44 \pm 0.009$, $v_6 = 0.043 \pm 0.037$, and $v_8 = -0.06 \pm 0.14$. Since v_6 is essentially zero, we place a two sigma upper limit on v_6 of 0.1%. Also, v_8 is zero, but the error is larger because the sensitivity decreases as the harmonic order increases.

Systematic uncertainties.—In both approaches, $v_4\{3\}$ and $v_4\{EP_2\}$, the nonflow effects are suppressed compared to the case where the fourth harmonic event plane is used. The remaining nonflow correlations, along with event-by-event flow fluctuations, are thought to be the major contributors to the systematic uncertainties. Background from secondary particles is expected to be less than 15%, and remaining acceptance effects are measured to be very small. All errors and limits quoted so far are statistical, and should be increased by the systematic uncertainties below.

From nonflow effects we estimate the relative systematic uncertainty in $v_4\{3\}$ to be about 20%. The largest contribution comes from situations in Eq. (3) where one particle is correlated with one of the other particles due to nonflow, and with the third particle via flow. Our estimate is based on the assumption that the entire difference in the published values [3] of $v_2\{EP_2\}$ and $v_2\{4\}$ is due to nonflow effects. Comparison of $v_4\{3\}$ to $v_4\{5\}$ leads to a similar estimate for this systematic error.

From nonflow effects we estimate the relative systematic uncertainty in $v_1\{3\}$ also to be about 20%. Our estimate is based on the assumption that our two-particle correlation value of v_1 using only the first harmonic event plane in the FTPCs, $v_1\{EP_1\}$, of about 3% is entirely due to nonflow effects.

The other effect important for the comparison of our results to theoretical calculations is event-by-event flow fluctuations. As was discussed [3], flow measurements are done by two or many particle correlations, resulting in not $\langle v_n \rangle$ but $\langle v_n^k \rangle^{1/k}$. If flow fluctuates event by event, it could lead to a difference between these two quantities. Fluctuations in the initial geometry of the collision at fixed impact parameter can account for the difference between $v_2\{EP_2\}$ and $v_2\{4\}$ [3], and also between $v_4\{EP_4\}$ and $v_4\{3\}$ [24]. Although the flow fluctuation contribution to $v_4\{3\}$ is greatly reduced, it still could lead to an effect of about a factor of 1.2 to 1.5.

Conclusions.—We have presented the first measurement of v_1 at RHIC energies. $v_1(\eta)$ is found to be approximately flat in the midrapidity region, which is consistent with microscopic transport models, as well as hydrodynamical models where the flatness is associated with the development of the expansion in the direction opposite to the normal directed flow. Within errors we do not observe a wiggle in $v_1(\eta)$ at midrapidity. The pseudorapidity dependence of v_1 in the projectile fragmentation region is very similar to that observed at full SPS energy. We observe a positive correlation between the first and second harmonics, indicating that elliptic flow is in-plane. This is the first direct measurement at RHIC of the orientation of elliptic flow relative to the reaction plane.

We have measured v_4 as a function of p_t, η, and centrality. We observe that v_4 appears to scale approximately as v_2^2, as a function of p_t, η, and centrality. v_6, although essentially zero, is not inconsistent with scaling as v_2^3. This is the first measurement of higher harmonics at RHIC, and it is expected that these higher harmonics will be a sensitive test of the initial configuration of the system, since they provide a Fourier analysis of the shape in momentum space which can be related back to the initial shape in configuration space. In fact, it has been emphasized that v_4 has a stronger potential than v_2 to constrain model calculations and carries valuable information on the dynamical evolution of the system.

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