Directed, elliptic and higher order flow harmonics of protons, deuterons and tritons in Au+Au collisions at \( \sqrt{s_{NN}} = 2.4 \text{ GeV} \)

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Flow coefficients \( v_n \) of the orders \( n = 1 - 6 \) are measured with the High-Acceptance DiElectron Spectrometer (HADES) at GSI for protons, deuterons and tritons as a function of centrality, transverse momentum and rapidity in Au+Au collisions at \( \sqrt{s_{NN}} = 2.4 \text{ GeV} \). Combining the information from the flow coefficients of all orders allows to construct for the first time, at collision energies of a
Heavy-ion collisions in the center-of-mass energy range of $\sqrt{s_{NN}} \approx 1 - 10$ GeV provide access to the properties of strongly interacting matter at very high net-baryon densities, which also define the characteristics of astrophysical objects like neutron stars \(^1\). Important information on this form of matter, e.g. on its Equation-Of-State (EOS), can be inferred from the measurement of collective flow \(^2\)\(^-\)\(^3\). The majority of the flow studies at SIS18 and AGS energies performed up to now were restricted to the analysis of directed and elliptic flow (for a review see \(^4\)\(^-\)\(^7\) and references therein). These correspond to the first ($v_1$) and second ($v_2$) order coefficients of the Fourier decomposition \(^8\) of the azimuthal angle $\phi$ distribution of emitted particles with respect to the orientation of the reaction plane. The latter is defined by the beam axis $\vec{z}$ of emitted particles with respect to the orientation of the colliding nuclei, which is given by the reaction plane angle $\Psi_{RP}$ \(^9\): \[
E \frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_t, y) \cos(n(\phi - \Psi_{RP})) \right).
\] (1)

However, it has been shown that important information can be extracted from an analysis of higher order flow coefficients. For instance, a comparison of the proton $v_3$ measured by HADES with UrQMD transport model calculations indicates that in particular $v_3$ exhibits an enhanced sensitivity to the EOS of the hadronic medium \(^9\)\(^-\)\(^10\). Other transport model calculations suggest that a non-vanishing fourth order coefficient ($v_4$) measured at center-of-mass energies of a few GeV can constrain the nuclear mean field at high net-baryon densities \(^11\). At high energies (RHIC and LHC) the measurements of higher order flow coefficients were decisive to determine the shear viscosity over entropy density $\eta/s$ of QCD matter at high temperatures \(^12\). Attempts have also been made to extract $\eta/s$ for dense hadronic matter at lower energies by employing transport models \(^13\)\(^-\)\(^16\) or hydrodynamical approaches \(^17\). Since these studies did not converge on conclusive results yet, input from measurements of higher order flow coefficients at low energies will be essential to further constrain the theoretical descriptions. In particular, they help to address the question whether matter at high net-baryon density produced in heavy-ion collisions at low energies can be described by hydrodynamical models. The authors of Refs. \(^18\) and \(^19\) have argued that, if the matter reaches thermal equilibrium, the fireball evolution should be governed by the laws of fluid dynamics which in turn should reveal itself by a distinct scaling property of $v_2$ and $v_4$: \[
\frac{v_4(p_t)}{v_2^2(p_t)} = \frac{1}{2}.
\] (2)

Measurements of this ratio at RHIC \(^20\)\(^-\)\(^21\) and LHC \(^22\)\(^-\)\(^24\) have found values that are roughly $p_t$ independent over a large interval for non-central events, but also significantly larger than the expected value of 0.5. This has been attributed to the combined effect of the initial eccentricity of the overlap zone \(^18\) and its fluctuations \(^25\). In the few GeV center-of-mass energy regime, the flow pattern is strongly affected by the presence of slow spectator nucleons. They interfere with the particle emission from the central fireball and will cause a distinct evolution of the relative contribution of odd and even flow harmonics as a function of rapidity.

In this letter we report first measurements of higher order flow harmonics (i.e. $v_n$ with $n = 3, 4, 5$ and 6) for protons, deuterons and tritons in fixed-target Au+Au collisions at $E_{\text{beam}} = 1.23$ A GeV, corresponding to a center-of-mass energy in the nucleon-nucleon system of $\sqrt{s_{NN}} = 2.4$ GeV.

A detailed description of the HADES experiment can be found in Ref. \(^26\). The spectrometer consists of six identical detection sections located between the coils of a toroidal superconducting magnet which cover polar angles between 18° and 85°. Each sector is equipped with a Ring-Imaging Cherenkov (RICH) detector followed by four layers of Multi-Wire Drift Chambers (MDCs), two in front of and two behind the magnetic field, as well as a Time-Of-Flight detector (TOF) (44° – 85°) and Resistive Plate Chambers (RPC) (18° – 45°). Hadrons are identified using the time-of-flight measured with TOF and RPC and the energy-loss information from TOF, as well as from the MDCs. Their momenta are determined via the deflection of the tracks in the magnetic field. The event plane angle (see Eq. (4) below) is calculated from the emission angles and charges of projectile spectators as measured in the Forward Wall (FW) detector. It consists of 288 scintillator modules which are read out by photomultipliers. The FW is placed at a 7 m distance from the target and covers the polar angles $0.33^\circ < \theta < 7.17^\circ$. The minimum bias trigger is defined by a signal in a 60 μm thick mono-crystalline diamond detector (START) \(^27\), which is positioned in the beam line. In addition, online Physics Triggers (PT) are used, based on hardware thresholds on the TOF signal and correspond to at least 5 (PT2) or 20 (PT3) hits in the TOF detector.
By comparing the measured TOF+RPC hit multiplicity distribution with Glauber Model simulations it has been estimated that the PT3 trigger is selecting about 43% of the total inelastic cross section of 6.83 ± 0.43 barn \cite{23}. This multiplicity is also used for the offline centrality determination. For this analysis the event sample is divided into four centrality intervals, each corresponding to 10% of the total Au+Au cross section at \( \sqrt{s_{NN}} = 2.4 \) GeV.

Tracks are reconstructed using the hit information of the MDCs. Several quality selection criteria are applied to assure a good matching of these tracks to the hits found in TOF and RPC which is essential for a good Particle IDentification (PID) via time-of-flight. Protons, deuterons and tritons are selected within windows of 2.5 \( \cdot \) \( \sigma(p) \) width around the corresponding particle velocity \( \beta \) expected for a given momentum \( p \). The resolutions \( \sigma(p) \) also depend on \( p \) and are parameterized accordingly. To suppress contaminations to the particle sample identified via time-of-flight, in particular the \(^4\)He contribution to the deuteron sample, the energy loss (dE/dx) measurements in the MDCs are used in addition. Phase space regions with a PID purity below 85% are excluded from the analysis. In high multiplicity Au+Au collisions reconstruction efficiencies depend on the local track multiplicities. Since collective effects will cause non-isotropies in the event shape, corresponding to local variations of the track densities and thus of the reconstruction efficiencies, a data-driven correction procedure depending on the track orientation relative to the event plane is applied.

The flow coefficients \( v_n \) can be determined by employing different methods. In the analysis presented here the azimuthal distributions of particle yields relative to the reaction plane. The first order event plane angle is then given by

\[
\tan \Psi_{EP} = \frac{Q_y}{Q_x}.
\]

The flow coefficients of all orders discussed here \( (n = 1 - 6) \) are all defined relative to \( \Psi_{EP} \), i.e. the first order event plane, as this measures the spectator event plane with the best resolution. The flow coefficients \( v_n^{obs} \) are obtained from the event averages

\[
v_n^{obs} = \langle \cos[n(\phi - \Psi_{EP})] \rangle.
\]

Finally, a corresponding event plane resolution correction is applied which takes the dispersion of \( \Psi_{EP} \) relative to \( \Psi_{RP} \) into account,

\[
v_n = \frac{v_n^{obs}}{R_n}.
\]

This resolution, defined as \( R_n = \langle \cos[n(\Psi_{EP} - \Psi_{RP})] \rangle \), is determined according to the procedure given in Ref. \cite{31}. Resulting values for the resolution correction of different order \( n \) as function of the centrality are shown in Fig. 1.

Systematic uncertainties of the measured flow harmonics \( v_n \) result from systematic effects in the reconstruction and selection of charged tracks, in the PID procedures, and in the corrections applied to \( v_n \). They are determined separately for each particle species \( (p, d, \text{ and } t) \), the order \( n \) of the flow harmonics \( v_n \), the centrality class and as a function of \( y_{cm} \) and \( p_t \) by varying selection criteria and parameters in the efficiency correction. Azimuthal asymmetries due to non-uniform acceptance and
reconstruction efficiencies can cause additional systematic uncertainties. These are estimated by comparing the results obtained for a fully symmetric detector (i.e. six sectors) with those where different combinations of sectors are deliberately excluded from the analysis. Furthermore, the analysis is performed on data recorded with a reversed magnetic field setting and for each day of data taking separately, in order to investigate whether any systematic trends appear in the course of the data taking period. No significant effects are observed in these cross-checks. A global systematic uncertainty arises from the event plane resolution correction. This is mainly caused by so-called “non-flow” correlations which can distort the event plane measurement. The magnitude of these systematic effects was evaluated by determining the event plane resolution correction for combinations of different sub-events separated in rapidity. The systematic effects

FIG. 2. The odd flow coefficients $v_1$, $v_3$ and $v_5$ for protons, deuterons and tritons in semi-central (20–30 %) Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV. The left column displays the $p_t$ dependence of $v_1$ (upper row), $v_3$ (middle row) and $v_5$ (lower row) in the rapidity interval $-0.25 < y_{cm} < -0.15$ ($v_1$ and $v_3$), respectively $-0.3 < y_{cm} < -0.1$ ($v_5$). In the right column the corresponding $y_{cm}$ dependences are presented. The values are averaged over the $p_t$ interval $1.0 < p_t < 1.5$ GeV/c ($v_1$ and $v_3$), resp. $1.0 < p_t < 2.0$ GeV/c ($v_5$). The dashed coloured curves represent fits to the data points (see text for details). Systematic errors are shown as open boxes. The selected $p_t$ and $y_{cm}$ values used for the right and left columns, respectively, are indicated by the grey areas.

FIG. 3. The even flow coefficients $v_2$, $v_4$ and $v_6$ for protons, deuterons and tritons in semi-central (20–30 %) Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV in the same representation as in Fig. 2 except that the $p_t$ dependences are shown for the rapidity interval $|y_{cm}| < 0.05$ ($v_2$ and $v_4$), respectively $|y_{cm}| < 0.1$ ($v_6$).

FIG. 4. Left panel: a three-dimensional representation of the proton emission pattern, $1/(N) \left(dN/d\phi\right)$, relative to the event plane according to the flow coefficients of the orders $n = 1$ – 6, as parametrized by the mid-rapidity symmetric fit functions shown in Figs. 2 and 3 for semi-central (20–30 %) Au+Au collisions. The shape corresponds to the $\phi$ dependent yield normalized by the $\phi$ averaged value, both integrated over the $p_t$ interval $1.0 < p_t < 2.0$ GeV/c. Right panel: slices at different forward rapidities. The thin circles display for orientation the values $1/(N) \left(dN/d\phi\right) = 0.5, 1.0$ and 1.5.
were thus estimated to be below 5% for the centralities 10 - 40%.

Figures 2 and 3 present an overview of the measured values for $v_1$ to $v_6$ for protons, deuterons and tritons. Here only the values for semi-central (20 - 30%) Au+Au collisions are shown as the event plane resolution corrections are smallest for this centrality range and the centrality dependences are weak, except for very central collisions. Shown is the $p_t$ dependence around mid-rapidity (even flow coefficients), respectively backward rapidity (odd flow coefficients), and the $\Delta y_{cm}$ dependence for values averaged over given $p_t$ intervals. The latter has been fitted with the following functions to illustrate the symmetry of the measurements: $v_{1,3,5}(\Delta y_{cm}) = a \Delta y_{cm} + b y_{cm}^2$ and $v_{2,4,6}(\Delta y_{cm}) = c + d y_{cm}^2$. The values for odd flow coefficients ($v_1$, $v_3$ and $v_5$) are consistent with zero at mid-rapidity, but exhibit a strong rapidity dependence, point-symmetric around mid-rapidity $\Delta y_{cm} = 0$. $v_1$ develops a prominent mass dependence ($|v_1|(p) < |v_1|(d) < |v_1|(t)$) when moving away from mid-rapidity. For larger rapidity values a mass hierarchy is also observable for $v_3$, which is, however, inverted with respect to $v_1$ ($|v_3|(p) > |v_3|(d) > |v_3|(t)$). Also for $v_2$ around mid-rapidity a clear mass ordering can be observed ($|v_2|(p) > |v_2|(d) > |v_2|(t)$) up to $p_t = 1.5$ GeV/$c$, as expected for a hydrodynamical evolution of the fireball. This mass hierarchy becomes even more pronounced when moving away from mid-rapidity. A similar, though less significant, mass difference is visible for $v_4$ ($|v_4|(p) > |v_4|(d) > |v_4|(t)$). We note that the integrated value for $v_2$ as measured here for protons agrees well with the world systematics, as compiled in [5, 6]. Also, we find the same $p_t$ dependence of $v_2$ at mid-rapidity as observed by FOPI [3] and KaoS [6].

The multi-differential measurement of all flow coefficients up to order 6 allows to construct a complete three-dimensional picture of the particle emission pattern relative to the event plane, as shown for the proton sample in Fig. 4. It is constructed by inserting values of $v_n$ for a given phase space interval from the parameterizations discussed above (see Figs. 2 and 3) into the cosine of the Fourier series: $1/(N) \langle dN/d\phi \rangle = 1 + \sum v_n \cos n \phi$. At mid-rapidity, the combination of all flow coefficients results in an almost elliptical shape centered around the beam axis with the odd coefficients being consistent with zero (see Fig. 2). The long axis of the elliptical shape is oriented along the $\phi = \pi/2$ direction, corresponding to out-of-plane emission. However, moving away from mid-rapidity a more asymmetric shape appears as the contribution of the odd coefficients increases. As a result, at very forward and backward rapidities the emission pattern develops an almost triangular shape, reflecting the complicated interplay between the effect of the central fireball pressure on the emission of particles and their subsequent interaction with spectator matter.

The ratio $v_4/v_2^2$ at mid-rapidity is shown in the left panels of Fig. 5. For protons a $p_t$ independent value slightly below 0.5 is observed for the three centralities intervals shown here, while for deuterons and tritons it is found to be systematically above 0.5, both also without significant $p_t$ dependence. However, these values are only reached around mid-rapidity as illustrated in the right panels of Fig. 5, which displays the rapidity dependence of $v_4/v_2^2$ in the $\Delta y_{cm}$ interval in which $v_2$ is negative and the effect of the spectator nucleons is less important. A rapid drop of the ratio is observed for the considered particle types when moving away from mid-rapidity, as the $\Delta y_{cm}$ distributions of $v_2$ and $v_4$ have different widths. Within the semi-central range between 10% and 40% no strong centrality dependence of the ratio $v_4/v_2^2$ is observed, as shown in Fig. 5. The very central interval (0 - 10%) is omitted from this comparison, as for this centrality the values of $v_2$ and $v_4$ are too close to zero to allow for the calculation of a meaningful ratio. The observation that $v_4/v_2^2$ is very close to the theoretical
expectation for an ideal fluid \cite{18,19,25} raises the question whether the properties of dense baryonic matter created in heavy-ion collision at these relatively low beam energies can be understood within the framework of hydrodynamic models. While the matter at high collision energies (RHIC and LHC), dominated in early stages by quark and gluon degrees of freedom, is well described by this kind of models as a near-perfect liquid with extremely low values of shear viscosity over entropy density $\eta/s$ \cite{12}, the situation at low energies is more complex. Here the degrees of freedom are hadrons, mainly baryonic resonances, and a one-fluid dynamical picture might not be fully applicable. In any case, the expected values for $\eta/s$ should be much higher \cite{13,14,16,17}, such that the appropriate dynamical model would be far away from an ideal fluid scenario. It should be pointed out that other ratios of flow coefficients, e.g. $v_3/(v_1v_2)$, were studied as well, but in these cases an independence of $p_t$ and particle type was not observed.

In summary, we report a multi-differential measurement of directed, $v_1$, and elliptic flow, $v_2$, and the first measurements of higher order flow coefficients ($v_3 - v_6$) for protons, deuterons and tritons in heavy-ion collisions in the few GeV center-of-mass energy regime. All flow coefficients are determined relative to a first order event plane measured at projectile rapidities. It is found that around mid-rapidity $v_1$ and $v_2$ have signs opposite to the one of $v_3$. The same sign change is observed between $v_2$ and $v_4$. Combining the flow coefficients $v_1 - v_6$ allows to construct for the first time a complete, multi-differential picture of the emission pattern of light nuclei as a function of rapidity and transverse momentum. For protons at mid-rapidity the ratio $v_4/v_2^2$ is found to be remarkably close to a value of 0.5, as expected in an ideal fluid scenario, while it is slightly higher for deuterons and tritons. A strong rapidity dependence of this ratio is observed for all light nuclei. Theory calculations within a hydrodynamic framework adapted to the description of baryon dominated matter are needed to investigate the question whether this kind of matter really exhibits a hydrodynamical behavior, at least in the last stages of the collision prior to freeze-out. The high precision information on higher order flow coefficients is a major step forward in constraining the EOS.

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