Azimuthal Anisotropies as Stringent Test for Nuclear Transport Models

P. Crochet\(^1\), F. Rami\(^1\), R. Donà\(^{1,2}\), J.P. Coffin\(^1\), P. Fintz\(^1\), G. Guillaume\(^1\), F. Jundt\(^1\), C. Kuhn\(^1\), C. Roy\(^1\), B. de Schauenburg\(^1\), L. Tizniti\(^1\), P. Wagner\(^1\), J.P. Alard\(^3\), A. Andronic\(^4\), Z. Basrak\(^5\), N. Bastid\(^3\), I. Belyaev\(^6\), A. Bendarag\(^3\), G. Berek\(^3\), D. Best\(^7\), J. Biegansky\(^8\), A. Buta\(^4\), R. Čaplar\(^5\), N. Cindro\(^5\), P. Dupieux\(^3\), M. Dželalija\(^5\), Z.G. Fan\(^3\), Z. Fodor\(^9\), L. Fraysse\(^3\), R.P. Freifelder\(^7\), A. Gobbi\(^7\), N. Herrmann\(^7\), K.D. Hildenbrand\(^7\), B. Hong\(^7\), S.C. Jeong\(^7\), J. Kecskemeti\(^9\), M. Kirejczyk\(^10\), P. Koncz\(^9\), M. Korolija\(^5\), R. Kotte\(^8\), A. Lebedev\(^6,11\), Y. Leifels\(^7\), V. Manko\(^11\), D. Moisa\(^4\), J. Mösner\(^8\), W. Neubert\(^8\), D. Pelte\(^12\), M. Petrovici\(^4\), C. Pinkenburg\(^7\), W. Reisdorf\(^7\), J.L. Ritman\(^7\), A.G. Sadchikov\(^11\), D. Schüll\(^7\), Z. Seres\(^9\), B. Sikora\(^10\), V. Simion\(^4\), K. Siwek-Wilczyńska\(^10\), U. Sodan\(^7\), K.M. Teh\(^7\), M. Trzaska\(^12\), G.S. Wang\(^7\), J.P. Wessels\(^7\), T. Wienold\(^7\), K. Wisniewski\(^7\), D. Wohlforth\(^8\), A. Zhilin\(^6\)

(FOPI Collaboration)

and C. Hartnack\(^{13}\)

\(^1\)Institut de Recherches Subatomiques, IN2P3-CNRS/ULP, Strasbourg, France

\(^2\)Istituto Nazionale di Fisica Nucleare, Legnaro, Italy

\(^3\)Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France

\(^4\)Institute for Physics and Nuclear Engineering, Bucharest, Romania

\(^5\)Ruđer Bošković Institute, Zagreb, Croatia

\(^6\)Institute for Theoretical and Experimental Physics, Moscow, Russia

\(^7\)Gesellschaft für Schwerionenforschung, Darmstadt, Germany

\(^8\)Forschungszentrum Rossendorf, Dresden, Germany

\(^*\)Present address : GSI, Darmstadt, Germany
Abstract

Azimuthal distributions of charged particles and intermediate mass fragments emitted in Au+Au collisions at 600 A MeV have been measured using the FOPI facility at GSI-Darmstadt. Data show a strong increase of the in-plane azimuthal anisotropy ratio with the charge of the detected fragment. Intermediate mass fragments are found to exhibit a strong momentum-space alignment with respect of the reaction plane. The experimental results are presented as a function of the polar center-of-mass angle and over a broad range of impact parameters. They are compared to the predictions of the Isospin Quantum Molecular Dynamics model using three different parametrisations of the equation of state. We show that such highly accurate data provide stringent test for microscopic transport models and can potentially constrain separately the stiffness of the nuclear equation of state and the momentum dependence of the nuclear interaction.

Keywords: Azimuthal distributions, nuclear equation of state, transport models, incompressibility, momentum dependent interaction.

PACS numbers: 25.75.Ld
I. INTRODUCTION

One of the major objectives in the investigation of high energy heavy ion collisions ($E_{\text{lab}} > 100\text{A MeV}$) is to provide information on the equation of state (EoS) of nuclear matter under extreme conditions of density and temperature. In this respect, collective flow effects of various ejectiles emerging from the reaction are of great interest since they are known as a sensitive probe of compression of nuclear matter [1]. These collective phenomena were predicted by nuclear hydrodynamical models [1,2] and experimentally identified in the eighties with the advent of the first generation of $4\pi$ detectors (Plastic Ball [3] and Streamer Chamber [4] at LBL-BEVALAC and the DIOGENE detector [5] at SATURNE) capable of full event by event characterisation. Different forms of nuclear matter flow were observed:

i) the directed sideward flow which appears as a sideward deflection of the emitted particles in the reaction plane [6,7];

ii) the squeeze-out effect which manifests itself as an enhanced emission out of the reaction plane [8,9]; and

iii) the so-called radial flow which has been more recently evidenced by the FOPI collaboration as an azimuthally symmetric expansion in highly central collisions [10].

Despite the extensive experimental studies [11] and the substantial theoretical progress [12–20] achieved so far, an unambiguous determination of the nuclear EoS from heavy ion collision studies is not yet at hand to date. Indeed, there remain still several difficulties in addressing this intriguing question:

- The extraction of information from experimental observables demands a thorough understanding of the reaction dynamics which can be possible only through prerequisite tests of nuclear transport models.

- The experimentally reconstructable observables are not uniquely sensitive to the incompressibility coefficient ($K$) characterising the nuclear EoS. Other effects such as the momentum dependence of the nuclear interaction (MDI) and the in-medium modification of the nucleon-nucleon cross section ($\sigma_{nn}$) play also an important role [12,13,17,21].
It is therefore crucial to disentangle the influence of the EoS from the one related to the other physical effects above mentioned.

- There are also several input parameters needed for the initialisation of transport codes \[22\] and somewhat arbitrarily fixed in the calculations, which might also influence significantly the theoretical predictions.

- The sensitivities of the experimental flow observables to the EoS (as well as MDI and in-medium $\sigma_{nn}$) are generally quite low \[13,23,24\], which requires highly accurate data. This implies in particular a good accuracy on the reaction plane reconstruction and low detector biases and inefficiencies.

- Available transport models underpredict composite particles yields \[25-28\]. Thus, a meaningful comparison between experimental flow observables and those predicted by the theory should be made on the basis of coalescence invariant quantities including the contributions of all emitted particles. This requires in particular the inclusion of intermediate mass fragments (IMF, $Z \geq 3$) which are known to carry larger amount of flow than do lighter particles \[29,32\] and which constitutes a non negligible fraction of the total mass of the system even at incident energies of a few hundred $A$ MeV \[26,32,34\].

Several experimental observables, corresponding to different projections of the triple differential cross section, have been introduced in order to characterise quantitatively the strength of the collective flow in heavy ion collisions \[8,35,36\]. One of these observables is the so-called “in-plane azimuthal anisotropy ratio” (defined in section IV) \[20\] which can be obtained from measurements of azimuthal distributions relative to the reaction plane. Theoretical calculations \[20,37\] in the framework of the Boltzmann-Uehling-Uhlenbeck (BUU) model \[38\] have shown the relevance of this observable as a sensitive quantity to pin down the nuclear EoS. Comparisons between data and BUU calculations were carried out for neutrons \[39,40\], but in this case the sensitivity to variations of the equation of state was found to be rather low. Recently, it was reported \[41\] that IMF, because of their strong alignment
along the flow direction \cite{29}, correlate much better with the value of $K$ used in the theory.

We report in this paper the first detailed experimental results on the in-plane azimuthal anisotropy ratio of light charged particles and IMF. The data were obtained from azimuthal distribution measurements carried out for the Au+Au reaction at several bombarding energies from 100 to 800\textit{A} MeV, using the FOPI facility at the SIS (GSI-Darmstadt) accelerator. Here we focus on the high incident energy of 600\textit{A} MeV where: i) the participant and the spectator products are better separated, ii) compressional and MDI effects are expected to be large \cite{12,17} and iii) high statistics dynamical model calculations are available \cite{12}. We find that the in-plane anisotropy ratio increases with the charge of the detected fragment. We show also that IMF exhibit a very pronounced alignment along the flow direction. The dependencies of the anisotropy ratio on the polar angle in the center-of-mass (c.m.) frame and the collision centrality are presented. They are compared to the predictions of the Isospin Quantum Molecular Dynamics (IQMD) \cite{43} model for different parametrisations of the equation of state. Simulated events are filtered through the FOPI acceptance and sorted in accordance to the adopted experimental procedure, which allows direct and realistic comparisons between data and model predictions. We show that the availability of such experimental data provide a stringent test for dynamical transport models. Based on FOPI data it has been shown that the shape of the fire-ball in central collisions depends sensitively on $\sigma_{nn}$ \cite{44}. Here, we emphasize the possibility to disentangle compressional and MDI effects on the basis of detailed azimuthal distributions in non central collisions for the participant as well as for the spectator source.

**II. EXPERIMENTAL SETUP**

The data were obtained in a complete experimental study of the Au+Au system at 6 beam energies going from 100 to 800\textit{A} MeV at the SIS (GSI-Darmstadt) accelerator using the FOPI/phase-I facility. As already noted, the present work is restricted to the incident energy of 600\textit{A} MeV. At this energy, about $10^6$ events were collected under the central trigger
condition \cite{45}. The latter was defined by adjusting the charged particle multiplicity to a value which corresponds to impact parameters less than 9\,fm in a clean-cut geometrical model. Most of the data which will be presented in the following were obtained from the analysis of these central events. Only those related to the centrality dependence will include events taken under the minimum bias condition \cite{45} (\textit{i.e.} events where at least 4 charged particles were detected in the angular range 7° \leq \Theta_{\text{lab}} \leq 30°). This large amount of available events allowed us to extract high statistics data.

The FOPI detector has been described in details in reference \cite{45}. Here, we recall briefly its different components and main features. At the incident energy considered in this paper, the setup consisted of a highly segmented Forward Wall of plastic scintillators, covering in full azimuth the laboratory polar angles (\Theta_{\text{lab}}) from 1.2° to 30°, complemented by a shell of thin plastic scintillator paddles mounted in front of it and subtending the \Theta_{\text{lab}} = 1.2° - 7° angular range. This device allowed us, event by event, to identify the nuclear charge and measure the vector velocities of most of the light charged particles and IMF (up to \(Z = 12\)) emitted in the forward c.m. hemisphere. Its high granularity (about a factor of three higher than the one of the earlier Plastic Ball detector \cite{3}) allowed high multiplicity events to be measured with a low multi-hit rate. The apparatus provides detailed and highly accurate measurements of triple differential cross sections for all charged particles with a very good accuracy on the reaction plane determination which is of crucial importance in the present work. Figure 1 illustrates the acceptance of the Phase-I configuration of the FOPI detector in the \((p_t^{(0)}, y^{(0)})\) plane, where \(p_t^{(0)}\) is the transverse momentum per nucleon normalized to the c.m. projectile momentum per nucleon (\(= 528.6\,\text{MeV/c}\)) and \(y^{(0)}\) denotes the rapidity normalized to the projectile rapidity in the c.m. frame. Solid curves represent the polar geometrical limits of the FOPI apparatus in the laboratory frame (\(\Theta_{\text{lab}} = 1.2°\) and 30°). The detection thresholds are indicated by the dotted curves in the case of \(Z = 3\) fragments. The dashed curves mark different c.m. polar angles \((\Theta_{\text{c.m.}})\) separated by 10 degrees. As it can be seen in Fig. 1, the apparatus allows undistorted measurements (free of detector biases) to be performed over a broad region of the forward c.m. hemisphere.
III. EVENT CHARACTERISATION

The study of azimuthal distributions requires a good event characterisation both in impact parameter and azimuthal orientation of the reaction plane. This is also of crucial importance when comparing the experimental data to theoretical predictions. In this respect, it is interesting to point out that a heavy system such as Au+Au has the advantage to offer a better determination of the collision geometry, both in centrality and reaction plane orientation, than lighter systems. In this section we will describe the procedure used in order to characterize the measured events and illustrate the performances of the FOPI apparatus.

To sort out the events according to their degree of centrality, we have employed the standard method based on the correlation between the multiplicity of the emitted particles and the impact parameter. The multiplicity distribution of charged particles measured in the angular range $7^\circ \leq \Theta_{\text{lab}} \leq 30^\circ$ exhibits a typical plateau for intermediate values and falls off for the highest multiplicities [26,33]. This distribution was divided into five intervals, in accordance to the procedure introduced in previous works [33,46]. The highest multiplicity bin (named PM5) starts at half the plateau value corresponding to $\simeq 2.5\%$ of the total reaction cross section and a maximum impact parameter of $\simeq 2.5 fm$ in a sharp cut-off approximation. The remaining multiplicity range was divided into four equally spaced intervals named PM1 to PM4. The limits of these event classes are given in Tab. I. In the following only events belonging to the PM2-PM5 bins are considered. An additional condition requiring the total detected charge to be larger than 30 was imposed in the analysis, in order to reduce the contribution of the background contamination from non target collisions. Within this condition the background contamination was estimated, by comparing measurements with and without target, to be less than 5% in the PM2 multiplicity range and negligible for higher multiplicity events. The mean impact parameters and the associated r.m.s. deviations listed in Tab. I were extracted from IQMD simulations, where the theoretical events
were passed through the detector acceptance and sorted in accordance to the above outlined procedure used for the data. By doing so, one can compare directly the experimental observables to the theoretical ones, even if the calculations do not reproduce the measured multiplicity distribution, which is the case of the IQMD model. The latter, as we will see in section V, underpredicts IMF multiplicities and overpredicts the overall charged particle multiplicities. This can be seen in Tab. I, where the lower limit of the PM5 bin for IQMD events is much larger (by 14 units) than the experimental one. However, when scaled to the lower limit of the PM5 bin, the theoretical multiplicity distribution is found to be in a fairly good agreement with the data in the range PM2-PM5. As shown in Tab. I, the charged particle multiplicity criterium covers a rather wide impact parameter range from \( <b> \simeq 3 \text{fm} \) to \( <b> \simeq 9 \text{fm} \).

The reconstruction of the azimuth of the reaction plane have been performed according to the transverse momentum analysis [35]. In the framework of this method, the reaction plane is determined, for each particle \( \mu \) in a given event, by the vector \( \vec{Q} \) calculated from the transverse momenta \( \vec{p}_t \) of all detected particles except the particle \( \mu \) in order to remove autocorrelation effects:

\[
\vec{Q} = \sum_{\nu \neq \mu} \omega_\nu \vec{p}_t^\nu
\]

M is the multiplicity of the event and \( \omega_\nu = 1 \) if \( y^{(0)} > \delta \), \(-1\) if \( y^{(0)} < \delta \) and 0 otherwise. \( \delta \), chosen equal to 0.5 in the present work, is a parameter introduced to remove mid-rapidity particles which are less correlated with the reaction plane. In order to estimate the accuracy on the reaction plane determination, due to finite number of particle effects and detector biases, we have used the method described in reference [35] which consists in randomly subdividing each event into two and calculating on average the half difference in azimuth (\( \Delta \Phi_R \)) between the reaction planes extracted from the two sub-events. \( \Delta \Phi_R \) gives an estimate of the dispersion of the reconstructed reaction plane with respect to the true one [35]. The results are displayed in Tab. I in terms of the standard deviation width \( \sigma(\Delta \Phi_R) \).
extracted from a gaussian fit to the $\Delta \Phi_R$ distributions. As can be seen, the reaction plane is, in all cases, rather well estimated, with a precision which varies typically from $\simeq 24^\circ$ to $\simeq 34^\circ$ depending on the event multiplicity. The data presented in this paper are corrected for these uncertainties on the reaction plane determination (see below).

IV. EXPERIMENTAL RESULTS

Azimuthal distributions are generally used to study the emission pattern of particles in the participant region (i.e. at mid-rapidity) of the collision. Instead of restricting the analysis to a narrow rapidity window centered around the c.m. rapidity, we have explored here the whole experimentally covered phase space (see Fig. 1). To select particles emitted in different regions of the phase space the analysis was carried out by imposing c.m. polar angle ($\Theta_{c.m.}$) gates to the data, as suggested in previous works [25,40]. The use of this $\Theta_{c.m.}$ binning was found to be more suited than using rapidity cuts because of the typical FOPI/phase-I acceptance (Fig. 1) which is limited to laboratory polar angles lower than $30^\circ$. Indeed by doing so, one can extract an accurate quantitative information from the measured triple differential cross sections over a broad region of the forward c.m. hemisphere where, as we will see in the following, the data are only very weakly affected by the detector cuts.

Typical examples of azimuthal distributions around the beam axis $Y(\Phi) = dN/d\Phi$ (where $\Phi$ is the azimuth of the emitted particle with respect to the azimuthal orientation of the reaction plane) of charged particles are displayed in Fig. 2 for the PM4 event class. These distributions were obtained for proton-like particles, i.e. by including all detected particles each being weighted with its charge. Different panels in Fig. 2 show results for different c.m. polar angle gates each 10 degrees wide except for the one around $90^\circ$ which was taken from $80^\circ$ to $100^\circ$. With increasing $\Theta_{c.m.}$, a drastic change in the azimuthal emission pattern is observed. At forward polar angles, the distribution exhibits a strongly enhanced in-plane emission along the sideward flow direction ($\Phi = 0^\circ$), while at large polar $\Theta_{c.m.}$ angles (approaching $\Theta_{c.m.} = 90^\circ$), one observes a clear preferential emission in the out-of-

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plane (\(\Phi = 90^\circ\) and \(\Phi = 270^\circ\)) direction corresponding to the squeeze-out effect. Thus, the shape of these azimuthal distributions reflects the strength of the collective motion for both the directed in-plane flow and the out-of-plane emission. In a previous paper [47] we have reported the results concerning the preferential out-of-plane emission. Here we focus on the in-plane anisotropy component.

In order to examine the data in a quantitative manner, we have extracted the magnitude of the in-plane anisotropy \(R\) for each \(\Theta_{\text{c.m.}}\) bin as:

\[
R = \frac{Y(\Phi)\big|_{0^\circ<\Phi<45^\circ} + Y(\Phi)\big|_{315^\circ<\Phi<360^\circ}}{Y(\Phi)\big|_{135^\circ<\Phi<225^\circ}}
\]

This definition of the in-plane anisotropy signal differs from the one used in earlier works [20,40], namely the ratio \(Y(\Phi)\big|_{\Phi=0^\circ} / Y(\Phi)\big|_{\Phi=180^\circ}\). This was dictated by statistics limitations for the theoretical IQMD calculations.

Fluctuations of the reconstructed reaction planes with respect to the true ones cause an attenuation of the experimentally observed anisotropies. To take into account this effect, we have proceeded in the following way [48] :

- We have first fitted a function of the form \(a_0 + a_1 \cos(\Phi) + a_2 \cos(2\Phi)\) to the measured \(Y(\Phi)\) distributions. The resulting fits are shown by the curves in Fig. 2.

- Then following [9], we have determined the corrected parameters:
  \[
  a'_0 = a_0 , \quad a'_1 = a_1 / (\langle \cos(\Delta\Phi_R) \rangle) , \quad a'_2 = a_2 / (2 < \cos^2(\Delta\Phi_R) > -1).
  \]

- Finally, we have extracted the corrected anisotropy ratios \(R\) by integrating in equation (1) the corrected fitting function.

The values of \(\cos(\Delta\Phi_R)\) and \(\cos^2(\Delta\Phi_R)\) were determined event wise and then averaged for each event class. The results are shown in Tab. II in the case of the \(40^\circ < \Theta_{\text{c.m.}} < 50^\circ\) gate for different centrality bins. As can be seen, the corrections become more important for peripheral events (PM2 bin) because of the relatively large dispersion in \(\Delta\Phi_R\).
Figure 3 shows the in-plane anisotropy ratio $R$ extracted from the data according to the definition in equation (1) and corrected for fluctuations of the reconstructed reaction plane, as a function of the polar angle $\Theta_{\text{c.m.}}$. The results were preselected by the charged particle multiplicity cut PM4. They are presented for different types of particles ($Z = 1$ to 4). The observed trend is characterized by a well defined maximum located at forward c.m. polar angles ($\Theta_{\text{c.m.}} \simeq 15^\circ$). The presence of this maximum is related to the bounce-off of the projectile remnants. For polar angles approaching $\Theta_{\text{c.m.}} = 90^\circ$, the anisotropy ratio tends to $R = 1$ as expected from symmetry reasons. Here, the azimuthal distribution exhibits a completely different pattern with an enhanced out-of-plane emission (Fig. 2) whose magnitude is commonly characterized by the squeeze-out ratio [9,49]. It should be pointed out that the overall trend, observed in Fig. 3, is qualitatively consistent with earlier data [50] obtained at much lower beam energy.

As can be seen in Fig. 3, with increasing fragment charge one observes larger azimuthal asymmetries with a more pronounced maximum whose location is shifted towards smaller polar angles. These features are more quantitatively illustrated in Fig. 4, where the maximum $R_{\text{max}}$ (top-panel) of the correlation $R$ versus $\Theta_{\text{c.m.}}$ and its location $\Theta_{\text{max}}$ (mid-panel) are plotted as a function of the charge of the detected fragment. $R_{\text{max}}$ and $\Theta_{\text{max}}$ were extracted by fitting a gaussian to the measured correlation between $R$ and $\log_{10}(\Theta_{\text{c.m.}})$. The resulting fits are shown, in the angular range where the fitting procedure was applied, by the dotted curves in Fig. 3. We have also displayed in Fig. 4 (lower-panel) the mean fragment multiplicities in the forward c.m. hemisphere ($y(0) > 0$). It is worth to note that IMF are still observed with quite large multiplicities at the relatively high incident energy of 600$\text{A}$MeV explored in the present work. We found [51] that IMF carry about 12% of the total detected charge in the case of the PM4 event class. It should be noted that for this class of events, a substantial fraction of IMF originates from the decay of the spectator source. When the latter source is selected the fraction of IMF remains nearly the same in the whole beam energy range from 250 to 800$\text{A}$MeV [52], what is in agreement with the universal behaviour of the spectator decay reported by the ALADIN collaboration [53]. The
observed dependence between $R_{\text{max}}$ and $Z$ (top-panel in Fig. 4) shows a roughly linear rise of the maximum anisotropy ratio with increasing fragment charge at least up to $Z = 4$. Above $Z = 4$, statistics in the data was not sufficient to extract accurate $R$ values, because of the very large anisotropies and the low multiplicities. On the other hand, the mid-panel of Fig. 4 shows that with increasing $Z$ the location $\Theta_{\text{c.m.}}^{\text{max}}$ of the maximum anisotropy moves towards lower values and seems to saturate.

The observed dependencies of $R_{\text{max}}$ and $\Theta_{\text{c.m.}}^{\text{max}}$ with the fragment charge, reflect the strong alignment of IMF along the flow direction, an effect which was qualitatively observed in the earlier Plastic Ball experiments [29] for the same Au+Au system at a beam energy of 200$A$ MeV. They are consistent with the increase of the sideward flow with the fragment size which was also reported in reference [29] and recently confirmed in more quantitative studies by several groups [30, 32, 51, 54]. The strong alignment of IMF could be qualitatively understood [29, 48] from a simple picture where the pure collective motion is superimposed upon the random thermal one: light particles being more sensitive to thermal fluctuations which tend to wash out their flow, while IMF being less affected by the undirected thermal motion are expected to be much more aligned along the flow direction.

V. COMPARISON TO IQMD MODEL PREDICTIONS

In this section we compare the experimental results to the predictions of the QMD model [13, 17, 43, 55] using the so-called IQMD version [13]. Besides the test of the IQMD model, our main aim here is to examine the possibility to disentangle compressional (EoS) and MDI effects on the basis of the present experimental results. It is worth to recall (see section I) that the theoretical predictions might also depend sensitively on other ingredients in the model such as the in-medium nucleon-nucleon cross section ($\sigma_{\text{nn}}$) which is not investigated in the present work. The possibility to constrain the in-medium $\sigma_{\text{nn}}$ has been discussed in previous works [13, 43]. We start with a very short description of the model and recall some of the typical features in the IQMD version. Then we discuss the influences of
the detector biases on the extraction of the in-plane anisotropy ratio. Finally, we confront the data to the model calculations for different parametrisations of the nuclear EoS.

A. The IQMD model

The Quantum Molecular Dynamics (QMD) model \cite{13,17,43,55} is a n-body theory which calculates the time evolution of intermediate energy heavy ion reactions on an event by event basis. Nucleons are represented as gaussian wave functions whose centroids are propagated according to the classical equations of motion and their width parameter $L$ is kept fixed. These wave packets are submitted to two and three body local Skyrme forces plus Yukawa and long range Coulomb potentials. An additional term describing the momentum dependence of the nuclear interaction (MDI) is included. The latter, which is computed from the momentum dependence of the optical p-nucleus potential, produces an additional transverse deflection of nucleons early in the reaction. The parameters of the density dependent Skyrme and MDI potentials are adjusted to reproduce the ground state properties of the infinite nuclear matter and to fix the choice of the incompressibility $K$ of the EoS. The numerical simulation of a complete event includes the initialisation procedure of projectile and target (see below), the propagation of nucleons through the previous potentials and the nucleon-nucleon interactions \emph{via} a stochastic scattering term. For each binary collision, the phase space distributions in the final stage of the scattering partners are checked to obey the Pauli principle, otherwise the collision is blocked. At the final stage of the reaction ($t = 200\, fm/c$), composite particles are formed if the centroid distances are lower than $3\, fm$.

The IQMD (Isospin Quantum Molecular Dynamics) \cite{13} is a QMD version which takes into account isospin degrees of freedom for the cross sections and the Coulomb interaction. This version uses a gaussian width fixed to $4L = 8.66\, fm^2$ for Au nuclei. The initialisation procedure consists in distributing randomly into a spherical phase space the position $r$ and the momentum $p$ of the gaussian centroids with $r \leq R$ and $p \leq p_F$, where $R = 1.12A^{1/3}$ ($A$ being the total nuclei mass number) and $p_F = 268\, MeV/c$ (Fermi momentum).
For the present work, the choice of this version, among other different realisations of the QMD model, is justified by the fact that IQMD is particularly suited for the analysis of nuclear matter collective effects. Our study is however relevant in a more general level since the major deviations about nuclear matter flow between the different QMD versions are now known to stem exclusively from the initialisation procedures and the gaussian widths.

B. Details about the calculations

IQMD events were computed for three different parametrisations of the nuclear EoS: i) a hard EoS \( K = 380 \text{A MeV} \) without MDI (H), ii) a hard EoS \( K = 380 \text{A MeV} \) with MDI (HM) and iii) a soft EoS \( K = 200 \text{A MeV} \) with MDI (SM). The calculations were performed for the full range of impact parameters from 0 to 14 fm. The number of simulated events was about 300-1000 per fm interval. It is important to mention that the theoretical events were triggered using the same centrality selection as for the data. In addition they were filtered through the acceptance of the FOPI/Phase-I detector including geometrical cuts and energy thresholds. The calculations were restricted to charged particles with \( 1 \leq Z \leq 12 \). Here, the azimuthal distributions were determined with respect to the true reaction plane (known in the model).

Before confronting the data to model calculations, let us make some comments on how the extraction of the anisotropy ratio \( R \) is influenced by the detector cuts. For this purpose, we used the IQMD (for both HM and SM parametrisations) events to compare the anisotropy ratios \( R \) before and after passing through the apparatus acceptance. The results are shown in Fig. 5 for the PM4 multiplicity bin, in terms of the ratio of unfiltered to filtered anisotropies, as a function of the c.m. polar angle. As clearly evidenced by this figure, the distortions caused by acceptance effects appear for very small \( \Theta_{c.m.} \) and for \( \Theta_{c.m.} > 65^\circ \). The values of \( R \) at small (large) \( \Theta_{c.m.} \) angles are mainly affected by the \( \Theta_{lab} = 1.2^\circ \) (\( \Theta_{lab} = 30^\circ \))
cut. Within $\simeq 4^\circ$ and $\simeq 65^\circ$, the ratio $R$ is only very little affected (less than 5% as one can see from Fig. 4) by the detector apparatus. It is worth to note that the effect is very similar for both HM and SM calculations. Similar observations were also made for the H parametrisation. In the following, the discussion will be restricted to the region $4^\circ < \Theta_{c.m.} < 65^\circ$ where a realistic confrontation of data to model predictions can be done with a high level of confidence, independently on how well the experimental filter simulates the different apparatus biases.

Using the same IQMD simulations (with a HM parametrisation), we have also investigated [48] the reliability of the method used in the previous section to correct the experimental anisotropy ratios for fluctuations of the reconstructed reaction plane. The validity of this method depends on how well the $< \cos(\Delta \Phi_R) >$ and $< \cos^2(\Delta \Phi_R) >$ quantities are estimated [4]. The latter have been calculated according to the method used for the data, i.e. by subdividing randomly each event into two and calculating the half difference in azimuth ($\Delta \Phi_R$) between the reaction planes extracted from the two sub-events. They are compared in Tab. III to the values obtained using the difference in azimuth ($\Phi_R - \Phi_{true}$) between the reconstructed reaction plane and the true one (known in the model). As one can see the two procedures lead to very similar results, except for the PM2 and PM3 multiplicity bins where differences of about 5% are found. This is due to the relatively small number of detected particles per event in such rather peripheral collisions. We have examined the influence of this effect on the extraction of the anisotropy ratio. We found that even in the least favourable case PM2, the value of the anisotropy ratio ($R = 3.34$) obtained within $\simeq 4^\circ$ and $\simeq 65^\circ$ by applying the procedure used for the data to the IQMD simulated events, remains close to the one ($R = 3.09$) extracted from the azimuthal distributions relative to the true reaction plane.
C. Data versus IQMD predictions

Tab. IV shows the mean multiplicities of different charged ejectiles in the PM4 bin for the data and for IQMD filtered calculations using a HM parametrisation. As one can see the model underpredicts by about a factor of 2.6 the experimental IMF multiplicities. The effect is even more important for \( Z = 2 \) particles (a factor of 4.3). It is found to be most pronounced for particles emerging from the participant region of the collision \([26,28,48]\). Similar deviations are observed for both SM and H parametrisations. This failure of the QMD model in reproducing the fragment multiplicities was also reported in other works \([25,27]\). It might be related \([27]\) to an artificial equilibration of the excited nuclear matter which in reality breaks up into several fragments. It is also known that the clusterisation probability depends strongly on the gaussian wave packets width \( L \) used in the model \([22]\). Therefore, in order to perform a meaningful comparison between data and model predictions \((i.e.\ with\ observables\ independent\ on\ the\ clusterisation\ process)\), one needs to reconstruct for both data and theoretical events coalescence invariant quantities. This is done, as described in section III, by including in the calculations of the anisotropy ratio all detected particles each being weighted by its charge. According to this procedure, the contribution of a given nucleon to the resulting observable is assumed to be independent of the fact that this nucleon is detected free or bound into a cluster. It has been shown in a recent work \([62]\) that the coalescence process accounts for many of the observed features of the phase-space densities of light fragments emitted from the participant region, and in particular the increase in sideward flow with fragment mass. All the anisotropy ratios \( R \) reported in what follows are presented in terms of such coalescence invariant quantities.

Figure 6 shows the ratio \( R \) as a function of \( \Theta_{c.m.} \) for semi-central events belonging to the PM4 multiplicity bin. Data are compared to the predictions of the IQMD model for the three parametrisations HM, SM and H. Data points are plotted with the overall systematic errors which have been estimated to 5\%. As can be seen, the general trends observed in
the data are qualitatively well predicted by the model irrespective of the parametrisation used in the calculations. Indeed, theoretical $R$ values reach a maximum around $\Theta_{c.m.} = 15^\circ$, mainly caused by the deflection of the projectile remnants, and tend toward 1 when $\Theta_{c.m.}$ approaches $90^\circ$. Now looking more quantitatively at the results, the following comments can be made. First, around $\Theta_{c.m.} = 15^\circ$ the experimental anisotropy ratio is better reproduced by a hard EoS without MDI (H). Both SM and HM parametrisations, including MDI effects, overestimate the data by about 40% and 60%, respectively. This is disturbing as the MDI should offer a more realistic description of the reaction since the proton-nucleus scattering data call for a momentum dependent interaction. Thus, the previous observation would suggest that the MDI is not properly treated in the model. Nevertheless it is important to point out that other parameters, like the in-medium $\sigma_{nn}$ or the ones related to the initialisation procedure, could also influence the calculations [22]. More detailed simulations performed with different sets of parameters should provide further information about this observation which remains difficult to be clearly interpreted at the present level of investigation. In particular, additional calculations made with a soft EoS without MDI would be helpful to draw conclusions about the effect of the MDI with respect to the stiffness of the EoS. It should be also noted that the use of coalescence invariant observables might be inappropriate at these small angles as the reaction mechanism behind the break-up and the evaporation of spectators is totally different from the freeze-out of a hot nucleon gas [17,38,55].

On the other hand, the in-plane anisotropy carried by particles emitted from the hot and dense central region of the collision (i.e. at large $\Theta_{c.m.}$ angles) shows a clear sensitivity to the stiffness of the EoS and almost no dependence to the MDI. Data are better reproduced by both hard EoS calculations (H and HM). The SM parametrisation leads to anisotropy ratios lower by about 15% than those predicted by the H and HM versions. This observation agrees qualitatively with the results of previous analysis done with other kind of in-plane flow observables [23,24].

Note that, by performing a similar analysis for the lower incident energies (100, 150, 250 and 400 $A$ MeV), we have obtained comparable trends but lower sensitivities, as expected in
Figure 7 shows the ratio $R$ as a function of the impact parameter. Experimental events were sorted here into 9 multiplicity bins (each 5 multiplicity units wide) from PMUL = 20 to 65. Theoretical $R$ values were extracted for the four large multiplicity bins PM2 to PM5 because of the low statistics. The impact parameter $b$ for the experimental data was determined with the IQMD model using the HM parametrisation (see Tab. I). The comparison between data and model predictions is shown for two $\Theta_{c.m.}$ regions: $4^\circ < \Theta_{c.m.} < 25^\circ$ (Fig. 7.a) and $45^\circ < \Theta_{c.m.} < 65^\circ$ (Fig. 7.b). The latter regions were taken from Fig. 6 which shows a sensitivity of $R$ to the MDI and to the stiffness of the nuclear EoS for small and large $\Theta_{c.m.}$, respectively. In the low polar angular domain (Fig. 7.a), the H parametrisation underestimates the experimental anisotropies, in particular at impact parameters above 5 fm; while both calculations including MDI (HM and SM) overpredict the data significantly. At large polar angles (Fig. 7.b), all three parametrisations underestimate the experimental results. This disagreement is, however, less pronounced with H and HM calculations.

The comparisons in Fig. 6 and Fig. 7 show that the general trends observed in the data are qualitatively predicted by the model irrespective of the parametrisation used in the calculations, but, on a more quantitative basis none of these three model versions (H, HM and SM) can consistently reproduce all of the experimental results. To understand these discrepancies, one needs more detailed theoretical investigations including explorations of the influence of other physical ingredients such as the in-medium nucleon-nucleon cross section and the sensitivity of the theoretical predictions to the input parameters (such as the gaussian width) used for the initialisation.

As illustrated in Fig. 7, the present data can potentially serve as a testing ground for the theory and should allow for disentangling compressional effects and those related to the momentum dependence of the nuclear force. Indeed in peripheral collisions, the anisotropy observable $R$ exhibits an almost pure sensitivity to MDI at forward angles (Fig. 7.a) where...
spectator matter is predominant; while at large $\Theta_{\text{c.m.}}$ angles \textit{i.e.} participant region) $R$ is purely sensitive to the stiffness of the nuclear equation of state (Fig. 7.b). This can be understood as follows. For central collisions, the overlap between nuclei produces a highly dense nuclear matter volume where the escaping particles are strongly representative of the degree of compression reached during the reaction. In addition, the high number of binary collisions between nucleons lowers their initial relative momentum and consequently the repulsive effect of the MDI. This is best seen by looking at the ratio $R$ at the more central collisions for large c.m. polar angles (Fig. 7.b), \textit{i.e.} by avoiding the contribution of the projectile remnants which remain influenced by the MDI since they feel a relative small compression as compared to the participant nuclear matter. With increasing impact parameters the overlap between nuclei \textit{i.e.}  compressional effects) and the number of nucleon-nucleon collisions decrease. Hence, in contrast to central collisions, the ejectiles feel a higher dependence to the MDI and a smaller dependence to the stiffness of the EoS. In this regard, it is worth noticing that we observe the most pronounced sensitivity to the MDI by looking at the $R$ ratio for small $\Theta_{\text{c.m.}}$ angles in peripheral collisions (Fig. 7.a) where particles are almost exclusively deflected by the initial contact of the colliding nuclei since compressional effects are quite low.

Although a definitive statement about the incompressibility of the nuclear EoS remains still elusive at the present stage, such comparisons have, nevertheless, the merit to illustrate the possibilities opened with the availability of the highly accurate data measured in the present experiment as stringent test for microscopic transport models, and in particular, the ability to unravel compressional and MDI effects.

\textbf{VI. SUMMARY AND CONCLUSION}

In this article, we reported the first detailed measurements of the in-plane azimuthal anisotropy ratio $R$ of light particles and IMF emitted in Au+Au collisions at an incident
energy of 600\,A MeV. Corrections for the finite resolution of the reaction plane reconstruction were applied. The study of the ratio $R$ was carried-out by scanning the phase space in terms of c.m. polar angle portions. This was found to be better adapted to the present detector acceptance as compared to rapidity selections. The $\Theta_{\text{c.m.}}$ dependence of the anisotropy ratio $R$ exhibits a well defined maximum, located at forward polar angles ($\Theta_{\text{c.m.}} \simeq 15^\circ$), which reflects mainly the bounce-off of the spectator remnants. We found that the larger the size of the detected particle, the stronger the magnitude of the azimuthal anisotropy and, therefore, the momentum space alignment with respect to the reaction plane.

Data were compared to the predictions of the IQMD model using three different parametrisations of the nuclear EoS. The comparison was performed in terms of the ratio $R$ determined as a coalescence invariant quantity, in order to avoid the problem of the lack of clusterisation in the IQMD model. It has been restricted to the c.m. polar angle domain $4^\circ < \Theta_{\text{c.m.}} < 65^\circ$ where detector acceptance effects on $R$ were estimated to be less than 5\%. We found that the general trends observed in the data are qualitatively predicted by the model irrespective of the parametrisation used in the calculations; but, on a more quantitative basis, none of these three model parametrisations (H, HM and SM) can consistently reproduce all of the experimental results. We show that, although a definitive statement in favour of one of the three parametrisations cannot be made at present, such comparisons have, nevertheless, the merit to illustrate the possibilities opened with the availability of the highly accurate data measured in the present experiment, over a broad range of impact parameters, as providing a stringent test for microscopic transport models. In particular, the ability to unravel compressional and MDI effects was clearly demonstrated: in the spectator region, the anisotropy observable $R$ exhibits an almost pure sensitivity to MDI, while in the participant region $R$ is purely sensitive to the stiffness of the nuclear equation of state.

Further detailed comparisons to microscopic transport model predictions, including explorations of in-medium effects on the nucleon-nucleon cross section, should help to provide deeper insight into the properties of hot and dense nuclear matter and the underlying equation of state.
ACKNOWLEDGEMENT

This work was supported in part by the French-German agreement between GSI and IN2P3/CEA and by the PROCOPE-Program of the DAAD.
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TABLES

TABLE I. Accuracy on the determination of the reaction plane for events measured under the PM2 to PM5 multiplicity conditions. $\sigma(\Delta \Phi)$ is extracted from a gaussian fit to the $\Delta \Phi$ distributions (see text). The limits of the different event multiplicity classes are given for both data (PMUL) and IQMD (PMULIQMD). For each event class, the mean impact parameter ($< b >$) and the corresponding r.m.s. deviation extracted from the IQMD model are given.

| Multiplicity bin | PM2   | PM3   | PM4   | PM5   |
|------------------|-------|-------|-------|-------|
| PMUL             | 16-31 | 31-46 | 46-62 | $\geq 62$ |
| PMULIQMD         | 19-38 | 38-57 | 57-76 | $\geq 76$ |
| $< b >$ (fm)     | 8.9 ± 0.9 | 6.7 ± 1.0 | 4.0 ± 1.4 | 3.0 ± 1.1 |
| $\sigma(\Delta \Phi)$ (deg.) | 34.5 | 23.6 | 24.7 | 30.0 |

TABLE II. In-plane anisotropy ratio $R$ before and after correction for fluctuations of the reconstructed reaction planes. The data are shown for the $40^\circ < \Theta_{c.m.} < 50^\circ$ cut. Errors correspond to systematical uncertainties. Statistical errors are lower than 1%.

| Multiplicity bin | PM2    | PM3    | PM4    | PM5    |
|------------------|--------|--------|--------|--------|
| $R$ not corrected | 2.32 ± 0.23 | 3.36 ± 0.24 | 3.02 ± 0.15 | 2.51 ± 0.13 |
| $R$ corrected    | 2.86 ± 0.29 | 3.94 ± 0.28 | 3.55 ± 0.18 | 2.96 ± 0.15 |
TABLE III. Values of $< \cos(\Phi_R - \Phi_{true}) >$, $< \cos \Delta \Phi_R >$, $< \cos^2(\Phi_R - \Phi_{true}) >$ and $< \cos^2 \Delta \Phi_R >$ obtained from filtered IQMD calculations. See text for more details.

| Multiplicity bin | PM2 | PM3 | PM4 | PM5 |
|------------------|-----|-----|-----|-----|
| $< \cos(\Phi_R - \Phi_{true}) >$ | 0.93 | 0.97 | 0.92 | 0.88 |
| $< \cos \Delta \Phi_R >$ | 0.87 | 0.94 | 0.92 | 0.88 |
| $< \cos^2(\Phi_R - \Phi_{true}) >$ | 0.90 | 0.94 | 0.89 | 0.85 |
| $< \cos^2 \Delta \Phi_R >$ | 0.85 | 0.90 | 0.87 | 0.81 |

TABLE IV. Mean multiplicities of different types of ejectiles emitted in the forward c.m. hemisphere for PM4 events class. Data are compared to different filtered IQMD model simulations. Errors represent statistical uncertainties including the r.m.s deviations of the distributions.

| $Z$ | $Z = 1$ | $Z = 2$ | $Z = 3$ | $3 \leq Z \leq 12$ |
|-----|--------|--------|--------|----------------|
| DATA | 44.03 ± 0.05 | 10.06 ± 0.02 | 1.72 ± 0.01 | 2.61 ± 0.01 |
| IQMD/HM | 61.89 ± 0.27 | 2.35 ± 0.02 | 0.45 ± 0.01 | 0.99 ± 0.01 |
FIGURES

FIG. 1. Illustration of the FOPI/Phase-I acceptance in the \((p_t^{(0)}, y^{(0)})\) plane for Au+Au collisions at 600\,A\,MeV (see text for more details).

FIG. 2. Azimuthal distributions, with respect of the reaction plane, including the contribution of all detected charged particles, each being weighted by its charge. The data are shown for the semi-central PM4 event class, for different \(\Theta_{\text{c.m.}}\) bins reported on the plots. Data points are larger than the corresponding statistical uncertainties. The curves are the results of the fit described in the text.

FIG. 3. In-plane anisotropy ratio \(R\) as a function of the polar angle \(\Theta_{\text{c.m.}}\), for different types of ejectiles. The data are shown for the PM4 event class. The error bars are of statistical origin. The dotted curves represents a gaussian fit to the correlation between \(R\) and \(\log_{10}(\Theta_{\text{c.m.}})\).

FIG. 4. Maximum in-plane anisotropy \(R^{\text{max}}\) (top-panel) and the corresponding polar angle \(\Theta_{\text{c.m.}}^{\text{max}}\) (mid-panel) as a function of the charge of the detected fragment. The lower panel shows the \(Z\) dependence of the mean multiplicity in the forward c.m. hemisphere. The data are shown for the PM4 event class. Error bars include statistical errors only. The curves are just to guide the eye. In the lower panel, data points are larger than the corresponding statistical uncertainties.

FIG. 5. In-plane anisotropy \(R\) obtained from unfiltered IQMD simulations divided by the one corresponding to filtered calculations, as a function of the c.m. polar angle \(\Theta_{\text{c.m.}}\). The calculations are shown for Au(600\,A\,MeV)+Au collisions preselected with the PM4 multiplicity cut. The full (dotted) line corresponds to a HM (SM) parametrisation of the nuclear EoS. The horizontal dashed lines indicate \(R = 1 \pm 0.05\) values. Statistical uncertainties in the IQMD values are lower than 2\%. 

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FIG. 6. In-plane anisotropy ratio $R$ as a function of the c.m. polar angle for semi-central (PM4) collisions. Data (circles) are compared to the predictions of the IQMD model with the parametrisations HM (solid curves), SM (dotted curves) and H (dashed curves). Theoretical values are calculated with respect to the orientation of the true reaction plane after application of the FOPI detector filter. Experimental values are corrected for the unaccuracy on the determination of the reaction plane (see text). The shaded zone corresponds to the polar c.m. angular domain where the data suffer significant distortions due to apparatus effects. Error bars on data points correspond to systematical uncertainties estimated to 5%. Statistical errors on theoretical points are lower than 2%.

FIG. 7. In-plane anisotropy ratio $R$ extracted in the c.m polar angular domains $4^\circ < \Theta_{\text{c.m.}} < 25^\circ$ (a) and $45^\circ < \Theta_{\text{c.m.}} < 65^\circ$ (b) as a function of the impact parameter ($b$). Data are compared to the predictions of filtered IQMD model calculations. Error bars on data points correspond to systematical uncertainties estimated between 5% and 10% depending on the collision centrality. The impact parameter is deduced from IQMD calculations using a HM parametrisation. Statistical errors on theoretical points are lower than 2%.
Figure 2

- $0^\circ < \theta_{c.m.} < 10^\circ$
- $10^\circ < \theta_{c.m.} < 20^\circ$
- $20^\circ < \theta_{c.m.} < 30^\circ$
- $30^\circ < \theta_{c.m.} < 40^\circ$
- $40^\circ < \theta_{c.m.} < 50^\circ$
- $50^\circ < \theta_{c.m.} < 60^\circ$
- $60^\circ < \theta_{c.m.} < 70^\circ$
- $70^\circ < \theta_{c.m.} < 80^\circ$
- $80^\circ < \theta_{c.m.} < 100^\circ$
Figure 3

\[ R \]

\[ \Theta_{\text{c.m.}} \text{ (deg.)} \]

- ○ Z=1
- ▲ Z=2
- ⊕ Z=3
- ★ Z=4
Figure 4

$R_{\text{max}}$ vs $Z$

$\theta_{\text{c.m.}}^{\text{max}}$ (deg.) vs $Z$

$dM/dZ$ vs $Z$

$y^{(o)} > 0$
Figure 7

$4^\circ \leq \Theta_{\text{c.m.}} \leq 25^\circ$

$45^\circ \leq \Theta_{\text{c.m.}} \leq 65^\circ$

- DATA
- IQMD/HM
- IQMD/SM
- IQMD/H

b (fm)