FRAGMENT FLOW IN Au+Au COLLISIONS

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Collective effects in Au + Au collisions at bombarding energies going from 100 to 800A MeV have been extensively investigated over the last years with the FOPI apparatus at GSI-Darmstadt. The main experimental results related to the different forms of nuclear matter flow in semi-central collisions are presented. The relevance of intermediate mass fragments as a probe of the collision dynamics and the collective motion is illustrated. The centrality dependence of both sideward flow and squeeze-out effects is examined over a broad range of impact parameters. Data are compared to Quantum Molecular Dynamics model predictions for different parametrisations of the nuclear equation of state. The onset of expansion phenomena in heavy-ion collisions is discussed on the basis of extrapolations of the measured excitation functions for both sideward flow and squeeze-out effects.

1 Introduction

One of the major goals in the investigation of high energy heavy-ion collisions is to learn about the bulk properties of strongly interacting systems at high temperatures and densities. Ultimately, one would like to determine the equation of state (EoS) of nuclear matter. The latter plays a crucial role in the dynamics of heavy-ion collisions and is also of fundamental importance in the study of astrophysical phenomena such as supernovae explosions and neutron star properties.

In this context, flow phenomena characterising the collective behaviour of nuclear matter are of particular interest since their magnitude reflects the amount of the effective pressure built up during the high density stage of the collision. The experimental identification of such collective effects was made possible by the advent, in the eighties, of 4π detectors capable of identifying and measuring the momenta of a large fraction of the particles emerging from the collision. One of the main results was the discovery by the Plastic Ball group [1] of the directed transverse flow of nuclear matter in finite impact parameter collisions. This finding was supplemented later on by the observation [2,3] of another form of collective expansion as an enhanced out-of-plane emission of mid-rapidity particles (the so-called squeeze-out). Since then, these collective effects were investigated in several experiments at different beam energy domains and large amount of data was obtained. However, despite the substantial progress accomplished in this field of research, no universal theoretical description of the properties of hot and dense nuclear matter has evolved so far. In order to constrain the various physical parameters in the theoretical models and verify their different assumptions, further detailed experimental studies were needed.

The FOPI collaboration has recently achieved a systematic study of both directed in-plane and squeeze-out flow components, providing a complete and accurate body of experimental data. We report here on the most relevant results with a particular emphasis on some specific aspects where FOPI experiments allow a significant advance to be made. The first aspect deals with intermediate mass fragments (IMF) whose production is intimately related to the collective motion and the collision dynamics. The availability of IMF flow data from the present work, while most experiments up to now have studied only light particles, is expected to yield valuable information on the stiffness of the nuclear matter equation of state. The second aspect concerns the impact parameter dependence of flow observables. To illustrate the relevance of the experimental results for testing adequaltely theoretical models, we present predictions of the Quantum Molecular Dynamics model for different parametrisations of the equation of state. We show in particular that detailed comparisons of flow data to dynamical model predictions over a wide range of impact parameters can help in disentangling the influences of compressional effects from those related to the momentum dependence of the nuclear interaction. The third aspect is related to the issue of the onset of expansion phenomena in heavy-ion collisions and the relative contribution of attractive and repulsive forces. The threshold energies of both directed in-plane flow and squeeze-out effects are estimated from the measured excitation functions. They are discussed in conjunction with the threshold energy for explosion obtained from the radial flow data [4,5].

2 Experimental procedure

The experimental data presented in this paper concern the Au + Au system at 6 incident energies $E_{LAB} = 100, 150, 250, 400, 600$ and $800A\ MeV$. They have been collected with the phase I setup of the FOPI apparatus at the SIS (GSI-Darmstadt) accelerator. In its phase I configuration, the FOPI detector consists of a highly segmented Forward Wall covering in full azimuth the laboratory polar angles between 1° and 30°, complemented by a Cluster Detector shell. The Forward Wall is made of 764 plastic scintillators providing an element identification of the reaction products through ΔE-time-of-flight measurements. The Cluster Detector shell consisting of 188 individual detector cells, is mounted in front of the Plastic Wall and behind a He-bag. This device combined with the Plastic Wall allows the dynamical detection range to be improved by lowering the detection threshold of IMF and extending the element identification up to Z=15. This setup measures simultaneously most of the light charged particles and IMF emitted in the forward c.m. hemisphere. Its high granularity allows high multiplicity events to be measured with a negligible multi-hit rate. The apparatus ensures a very good azimuthal symmetry, an important feature for the reconstruction of the reaction plane and azimuthal distribution measurements. A more detailed description of the different components of the FOPI apparatus can be found in reference [6].

3 Event characterization

The investigation of collective effects in heavy-ion collisions requires a good event characterization both in impact parameter and azimuthal orientation of the reaction plane.

To sort out the measured events according to their degree of centrality, we used the standard method [7,8] based on the correlation between the multiplicity of emitted particles and the impact parameter. Simulation studies [9] in the framework of the Quantum Molecular Dynamics (QMD) model show that with the FOPI setup, the multiplicity selection criterium (PMUL) allows the coverage of a wide range of impact parameters (from ~ 4 to $\sim 10 fm$). Other criteria, such as the ratio ERAT [4] of the transverse to the longitudinal energy, were also used to discriminate more central events ($b < 4fm$).

To reconstruct the azimuth of the reaction plane, we employed the well known transverse momentum analysis procedure introduced by Danielewicz and Odyniec [10]. The dispersion of the reconstructed planes due to finite number of particle effects and detector biases was found to vary typically between $\sigma(\Delta\Phi) \simeq 20°$ and $40°$ depending on the bombarding energy and the collision centrality. Its influence on the flow observables is taken into account for most of the results presented in this paper.

4 The relevance of IMF in flow studies

The first FOPI data [8,11,12] revealed that in the incident energy domain under consideration (100 to $800A\ MeV$), a large fraction of the nuclear matter emerging from the collision is emitted in the form of IMF. It was shown that at $E_{LAB} = 100A\ MeV$, IMF constitute a large fraction (about 40%) of the total initial charge in central Au+Au collisions. Furthermore IMF exhibit higher sensitivity to both geometrical and dynamical features of the collision and their production mechanism is intimately connected to the collective expansion of the emitting nuclear system. For these reasons, a particular emphasis was placed in the present work on the contribution of IMF to the collective flow and the interplay with the measured multiplicities.

Fig.1a shows the dependence of the flow parameter ($F_S = d\left\langle \frac{p^x}{A} \right\rangle / d\left(\frac{y^{cm}}{y_P^{cm}}\right)$ at $y^{cm}/y_P^{cm} \simeq 0$) as a function of the charge of the detected fragment. The data are presented at an incident energy of $400A\ MeV$ and for semi-central collisions (PM4 event class [8]) corresponding to an average impact parameter of $\sim 5fm$. As can be seen, the flow parameter increases monotonically with the charge of the detected fragment up to Z=3 which is consistent with the previous measurements of the Plastic Ball collaboration [13] and those more recently reported by the EOS group [14]. Our data show in addition that above Z=3 the flow parameter becomes nearly independent of the size of the fragment. This trend seems to

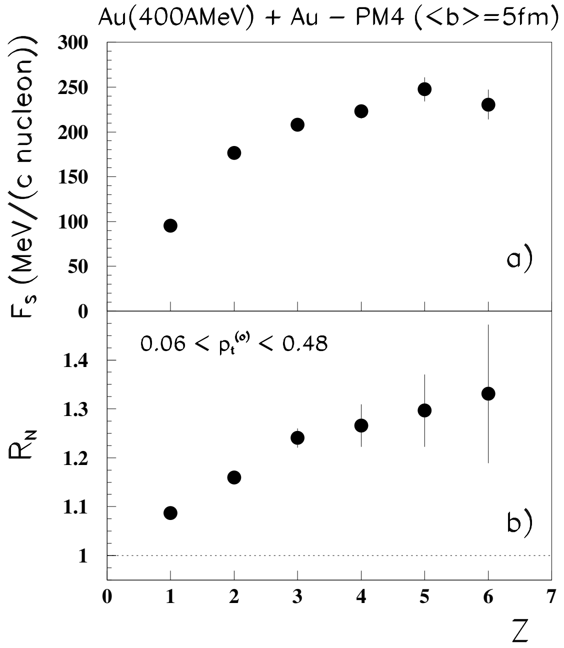

Figure 1: Flow parameter F_S (a) and anisotropy ratio R_N (b) as a function of the charge of the detected fragment. The data are shown for semi-central events (PM4 class), at a bombarding energy of $400A\ MeV$. Error bars correspond to statistical uncertainties.

be common to all flow observables. Indeed, a very similar behaviour is observed (Fig.1b) for the squeeze-out ratio R_N defined as the ratio of the number of particles emitted out-of the reaction plane to the number of particles emitted in the reaction plane. The ratio R_N was extracted [15] from the measured azimuthal distributions (around the beam axis) of mid-rapidity particles within a transverse momentum cut $0.06 < p_t^{(0)} < 0.48$ ($p_t^{(0)} = p_t/p_p^{cm}$, where p_p^{cm} is the projectile c.m. momentum per nucleon). This condition was introduced in order to avoid distorsions due to detector biases.

This dependence on the particle size of both sideward and squeeze-out flow components can be intuitively understood in the framework of a simple picture of an expanding thermal source where particles of different masses share the same thermal energy but their collective energy is proportional to their mass. Light particles would be subjected to large thermal fluctuations which tend to reduce their effective flow, while heavier fragments are much less affected by the random thermal motion and their flow would be therefore preserved. Monte-carlo simulations based on this idea reproduce [9,16] quite well the observed trend including the constant value obtained for the heaviest fragments.

In Fig.2 one can see the comparison of data to the predictions of the Isospin Quantum Molecular Dynamics (IQMD) model [17] for 2 different parametrisations of the nuclear equation of state : i) a hard ($K = 380MeV$) momentum-dependent potential (HM) and ii) a soft ($K = 200MeV$) momentum-dependent potential (SM). The data are expressed here in terms of the mean in-plane transverse momentum per nucleon $< p_x/A >$ versus the c.m.

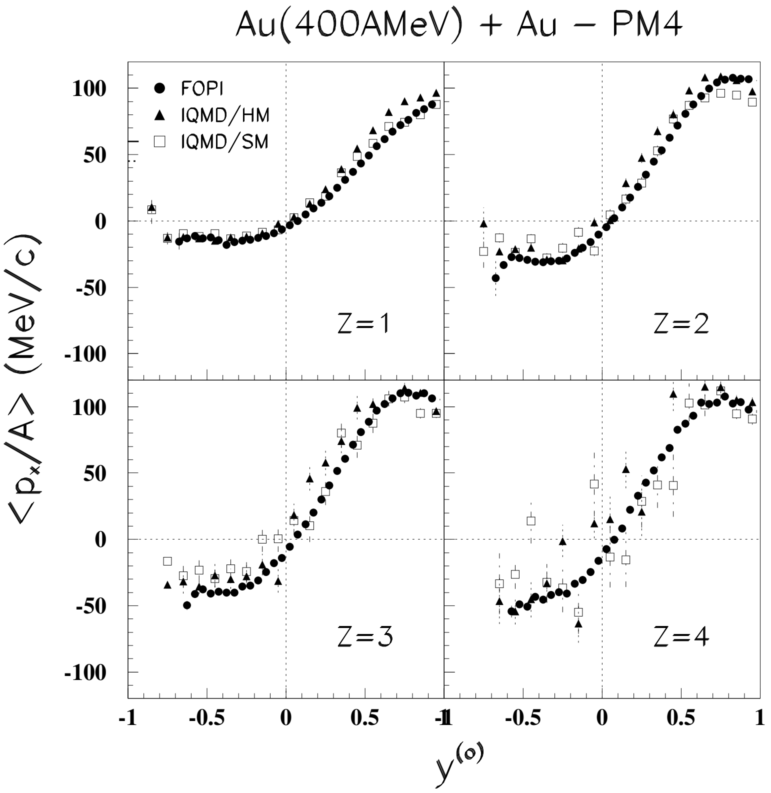

Figure 2: Mean in-plane transverse momentum per nucleon as a function of the normalised rapidity for semi-central (PM4) events at $400A\ MeV$. Data are compared to filtered IQMD simulations for two different parametrisations HM and SM (see text). Both data and calculations are corrected for fluctuations of the reconstructed reaction plane (correction factors were typically ~ 1.10). Error bars include only statistical errors.

rapidity normalised to the c.m. projectile rapidity ($y^{(0)}$). Events generated with the IQMD code were filtered through the FOPI detection filter and analysed in the same way as for the data, which allows direct comparisons between data and model calculations.

The results show that, regardless of the parametrisation used in the calculations, the general trends observed in the data are qualitatively well predicted by the model. The latter also predicts the increase of the sideward flow with the fragment charge. As expected the hard equation of state generates more flow than the soft one, but differences between both calculations are rather small for Z=1,2 particles (for Z $\geq$ 3 statistics is very low), and cannot be used to draw any conclusion on the basis of the comparison with data. This can be illustrated more quantitatively from the values (Table 1) of the flow parameter extracted for both HM and SM calculations in the case of Z=1,2 particles. The ratio F_S(HM)/F_S(SM) is larger for Z=2 (1.14) than for Z=1 (1.09) particles. This ratio is expected to be even larger for IMF [a] because of their stronger sensitivity to collective effects. Similar predictions were reported recently by Zhang and Gale [18] in the framework of BUU calculations where the

[a] Statistics for IMF was insufficient to extract reliable values of the slope at mid-rapidity.

	$Z=1$	$Z=2$
HM	132.4 ± 3.1	236.1 ± 13.8
SM	121.4 ± 5.0	206.7 ± 14.6

Table 1: Flow parameter F_S extracted from the IQMD calculations presented in Fig.2.

dependence of the sideward flow, evaluated in terms of the maximum in-plane azimuthal anisotropy, on the stiffness of the equation of state was investigated. It was found that for IMF the magnitude of the sideward flow increases by a factor of ~ 1.6 when K goes from $200 MeV$ (soft) to $380 MeV$ (hard), while in the case of nucleons this increase is much less important (see Fig.3 in reference [18]). This demonstrates the relevance of IMF flow observables as a promising tool to constrain the stiffness of the nuclear equation of state.

However the extraction of information on the equation of state from such detailed comparisons (Fig.2) between data and model predictions remains questionable as far as the model does not explain the experimental fragment multiplicities. As can be seen in Fig.3, the IQMD model overpredicts the multiplicity of Z=1 particles and underpredicts the production of heavier particles ($Z \geq 2$). One observes about a factor of 4 difference between data and model predictions for Z=3 fragments. IMF are extracted in the calculations by applying a minimum spanning tree procedure [19] where two nucleons are considered to be bound in a cluster if the centroids of their wave packets have a spacial distance lower than the correlation length d_0 (taken as $d_0 = 3fm$ in the IQMD code).

This failure of the QMD model in reproducing the measured IMF multiplicities (Fig.3) was also reported in other works [20]. According to recent theoretical developments [21], the lack of IMF in the QMD model might be caused by an artificial equilibration of the excited spectator matter which in reality breaks up into several fragments. It was also shown [22] that the clusterisation probability in QMD models is influenced by the value of the wave packet gaussian width used in the calculations.

These two aspects, IMF production and flow, are closely connected. Indeed, if the nucleons comove in the same direction they will have a large probability to form a cluster. While, in the case where the nucleons have large random thermal velocities, the probability to form a cluster will be small. This interplay between IMF production and the collective motion calls for theoretical descriptions capable of reproducing simultaneously both flow and fragment multiplicities.

5 Impact parameter dependence of flow observables

Both sideward and squeeze-out flow components depend quite strongly on the collision geometry. It is therefore important to have access experimentally to the correlation between the underlying observables and the impact parameter. Simulation studies [5,9] have shown

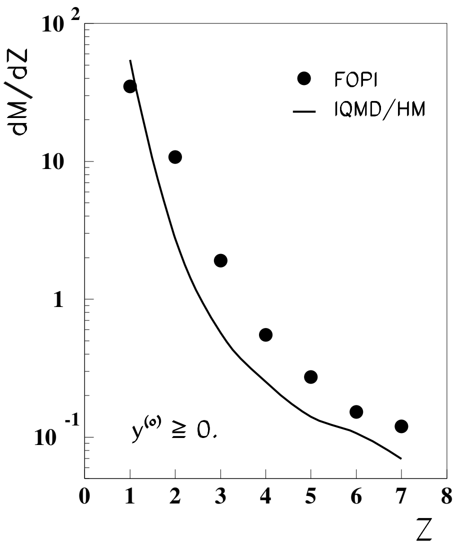

Figure 3: Mean multiplicity as a function of the fragment charge, for semi-central (PM4) events at $400A\ MeV$. Data (points) are compared to filtered QMD calculations (curve) with a HM parametrisation. The statistical errors in the data are less than 1%. Those in the calculations vary from $\sim 0.5\%$ to $\sim 5\%$ as the fragment charge increases.

that, in the framework of the present experiment, the PMUL and ERAT centrality criteria (see section 3) complement each other, each providing an access to different ranges of impact parameters : from $\sim 3.5fm$ to $\sim 10fm$ and $\sim 1fm$ to $\sim 7fm$ for PMUL and ERAT, respectively. Thus, by combining both criteria it was possible to explore the whole b domain from $\sim 1fm$ to $\sim 10fm$.

This is illustrated in the left panel of Fig.4, where the directed in-plane transverse momentum p_x^{dir} (defined as $p_x^{dir} = \frac{1}{A}\sum_i sign\left(y_i^{(0)}\right) \times p_x^i$) extracted from the $400A\ MeV$ measurements, is plotted as a function of the impact parameter. The p_x^{dir} observable includes the contributions of all detected particles each being weighted with its charge. The impact parameter was evaluated within a geometrical clean-cut model on the basis of the PMUL binning (open circles) and the ERAT selection (full circles). It is interesting to note the remarkable consistency between both PMUL and ERAT sets of data points, in particular in the overlap region (3.5 to $7fm$).

The observed correlation (Fig.4) between p_x^{dir} and b exhibits the expected behaviour with a well pronounced maximum at intermediate impact parameters (around $3.5fm$) and vanishing sideflow at both the low and high b ends. A similar trend is found at incident energies of 150 and $250A\ MeV$ [5]. As shown in the right panel of Fig.4, IQMD model predictions agree quite well with the overall trend observed in the data. More detailed comparisons with the different model versions (HM, SM and H) require the inclusion of apparatus biases and inefficiences as well as the distorsions due to fluctuations of the reaction plane (data shown in Fig.4 are not corrected for these effects). This should be done carefully as the influence of the above mentioned effects could be comparable to

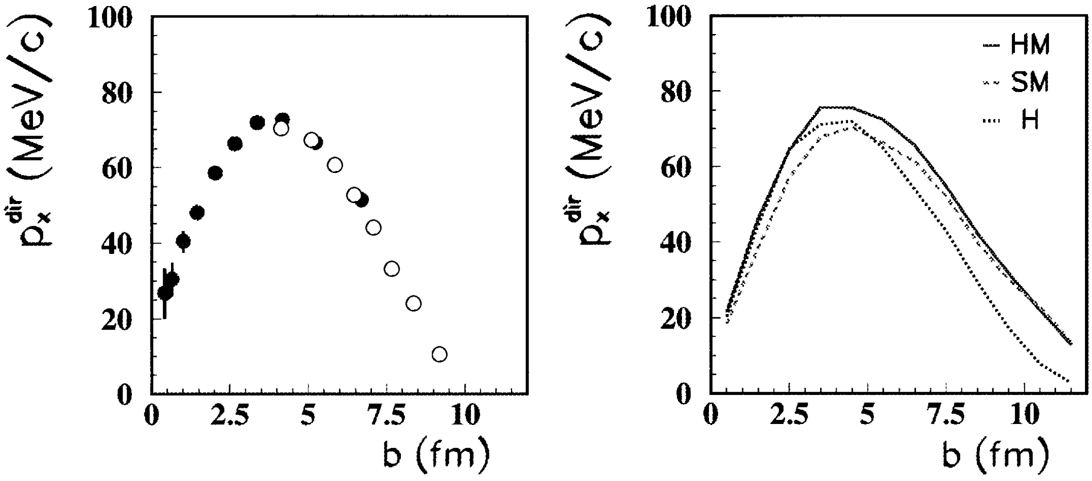

Figure 4: Directed in-plane transverse momentum p_x^{dir} as a function of the impact parameter. Left panel : The data are shown for the bombarding energy of $400A\ MeV$. The impact parameter was evaluated here within a geometrical clean-cut model using the PMUL criterium (open circles) and the ERAT selection (full circles). Error bars correspond to statistical errors only. Right panel : The predictions of IQMD calculations are displayed for different parametrisations of the EoS.

differences between two different parametrisations in the model. Such comparisons should contribute to constrain separately both EoS and momentum dependent interaction (MDI) effects. Indeed according to the IQMD calculations shown in Fig.4, in the low b region p_x^{dir} is sensitive to the EoS and insensitive to MDI, while at high b values there is almost no sensitivity to the EoS but a quite strong dependence on MDI. The low sensitivity to the stiffness of the nuclear EoS (the difference between HM and SM curves is less than 10%) could be enhanced by taking advantage from the flow of IMF as we have seen in the previous section.

Now we turn to the centrality dependence of the squeeze-out effect. The anisotropy signal R_N is displayed in Fig.5 as a function of the impact parameter, at 4 incident energies going from 100 to $400A\ MeV$. The ratio R_N was extracted for proton-like particles, i.e. including all protons whether free or bound in cluster, under the condition [15] $0.40 < p_t^{(0)} < 0.55$. The impact parameter was estimated in the same way as for the sideward flow data (Fig.4). But here only the PMUL binning was used.

The correlation between the ratio R_N and the impact parameter shows a very different trend when the incident energy rises from 100 to $400A\ MeV$. At the lowest bombarding energy ($100A\ MeV$), a clear change in the emission pattern is evidenced : with decreasing impact parameter, one observes a transition from a preferential in-plane emission ($R_N < 1$) to the squeeze-out effect characterized by an enhanced out-of-plane emission ($R_N > 1$). Similar observations were reported very recently by Tsang et al [23] for the same Au+Au sys-

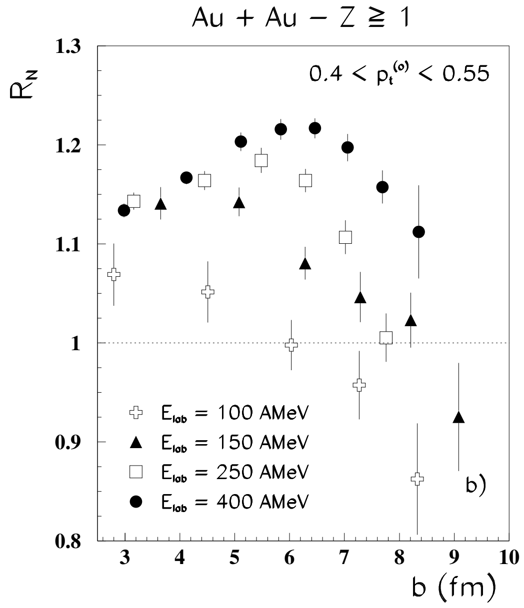

Figure 5: Anisotropy ratio R_N as a function of the impact parameter b, at different bombarding energies. The signal is determined with the $p_t^{(0)}$ cut indicated in the figure. Error bars correspond to statistical uncertainties only.

tem. This transition will be discussed in the next section. With increasing beam energies, the shape of the correlation evolves gradually towards a bell-shaped distribution whose maximum is located at intermediate impact parameters (close to $6fm$). This maximum is consistent with an expansion-shadowing picture, i.e. an expansion of the compressed matter in the central region of the collision which is hindered by the presence of cold spectator remnants. It is worth noting that QMD calculations for neutrons [24] predict a similar bell-shaped correlation with a maximum around $7fm$.

6 Onset of collective expansion

The lowest beam energy ($100A\ MeV$) explored in the present work lies in the energy domain where changes from low energy processes dominated by the attractive mean field to high energy mechanisms governed by individual nucleon-nucleon collisions are expected. Signatures of this transition were suggested from the observation of a vanishing in-plane flow [25–27] caused by the balance between attractive and repulsive forces. The incident energy (the so-called balance energy E_{BAL}) where the in-plane flow disappears was extracted for different colliding systems [25–27] and its value was found [28] to be particularly sensitive to the in-medium nucleon-nucleon cross section. Recent experimental results reveals also a change in the azimuthal emission pattern of mid-rapidity particles from an in-plane to an out-of-plane distribution [29,30]. The beam energy where this transition takes place (termed E_{TRA}) provides another observable related to the interplay between attractive and repulsive forces.

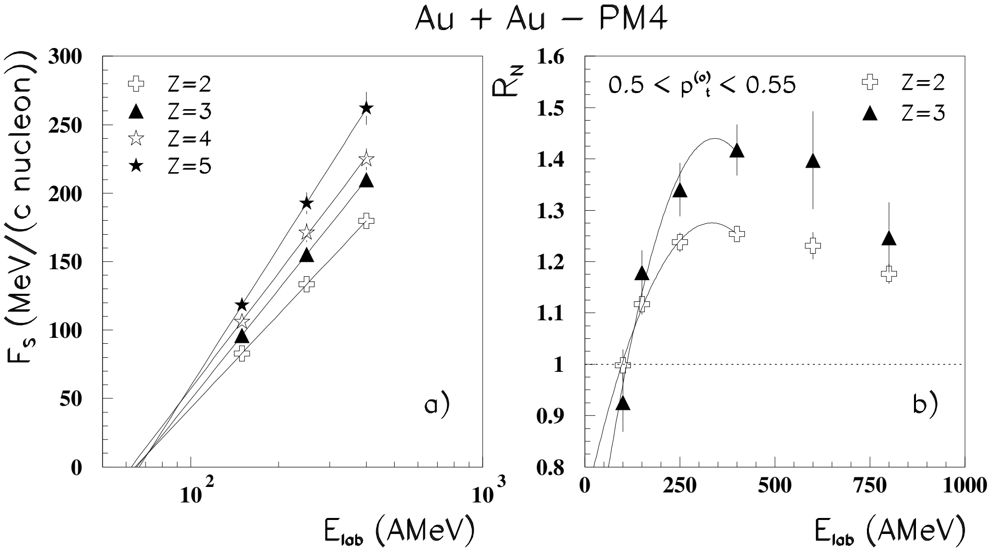

Figure 6: Left panel : Excitation functions of the flow parameter measured for different particles (Z=2 to 5) in semi-central Au+Au collisions (PM4 event class). The experimental points are corrected for fluctuations of the reaction plane. The lines correspond to logarithmic fits to the data. Error bars include statistical uncertainties only. Right panel : Excitation functions of the R_N anisotropy ratio for Z = 2 and 3 particles emitted in semi-central (PM4) collisions. The signal is extracted under the $p_t^{(0)}$ condition indicated in the figure. Error bars correspond to statistical uncertainties only. The curves show a fit to the data using a second order polynomial function.

The availability in the present experiment of accurate excitation functions for sideward [9] flow and azimuthal distributions [9,31,32] allows us to extract estimates of both balance and transition energies. In addition, the ability of the FOPI detector to measure a wide range of impact parameter collisions (section 3) offers the possibility to investigate the impact parameter dependence of E_{BAL} and E_{TRA}, an aspect which was recently recognized to be crucial in this kind of studies [33]. In this regard, a heavy system such as Au+Au has the advantage to be well suited since the collision geometry can be better determined than in the case of lighter systems. It is also worth noting that, in contrast to most experiments until now, the values of E_{BAL} and E_{TRA} are evaluated here from the measurements of fragments which carry a cleaner information on the magnitude of the collective motion (section 4).

Fig.6a shows the flow parameter extracted for different particles (Z = 2 to 5) as a function of the logarithm of the incident energy for the 3 points in the energy region from 150 to $400A\ MeV$. In this representation the data points exhibit a linear dependence. This trend is consistent with previous results reported by Zhang et al [34]. An extrapolation with straight lines allows us to estimate the balance energy (intersection with the abcissa) for different types of particles. The extrapolation for Z=3 fragments leads to an intersection energy of $E_{BAL} = 65 \pm 4A\ MeV$ for semi-central events corresponding to the PM4 bin. The resulting values for the other particles are the same within statistical uncertainties as the one obtained for Z=3. This indicates that the balance energy is independent of the size of the detected particle.

It is worth noting that for a heavy system like Au+Au, because of the strong Coulomb repulsion the overall forces are always repulsive [33]. Nevertheless the extrapolation from the high energy region where Coulomb contribution is negligible can yield an observable related to the competition between attractive and repulsive nuclear forces, which can be compared to the balance energy obtained for lighter systems (where Coulomb repulsion is much weaker). The value of $E_{BAL} = 65 \pm 4A\ MeV$ obtained here is in quite good agreement with the systematics of the balance energy as a function of the mass of the combined projectile-target system [27].

The transition energy E_{TRA}, corresponding to an azimuthally symmetric distribution ($R_N = 1$), can be similarly evaluated from the excitation functions of the anisotropy ratio R_N. The latter was extracted for high p_t particles (which are more sensitive to the collective motion) by imposing a p_t cut whose limits, indicated in Fig.6b, were dictated by acceptance and statistics considerations. Technically, the data points in the beam energy range from 100 to $400A\ MeV$ were fitted with a second order polynomial function and the value of E_{TRA} was determined at the intercept of $R_N = 1$ with the curves (Fig.6b). It should be pointed out that the analytic form of the fitting function does not significantly affect the value of the extracted transition energy [31]. The resulting value ($E_{TRA} \simeq 100A\ MeV$) for the PM4 event class seems to be also independent on the type of the detected particle. This value is somewhat larger than the one ($65A\ MeV$) obtained for the onset of the sideward flow. This finding agrees with recent theoretical calculations for the Ca+Ca system [33] and could be explained by the fact that at the balance point the compression is not high enough to generate an enhanced out-of-plane emission.

The transition energies obtained from extrapolations of the measured excitation functions (Fig.6.b) for four different charged particle multiplicity bins are plotted in Fig.7 (full triangles) as a function of the corresponding mean impact parameter determined in the framework of the QMD model. The data exhibits a clear dependence on the collision centrality : we observe an increase of E_{TRA} with increasing impact parameters. This trend may indicate that the transition phenomenon is related to the energy to be deposited into the system in order to overcome the attractive nuclear forces. When going from peripheral to central collisions, the energy deposit becomes larger and the transition is therefore expected to take place at a lower incident energy. With this in mind, it is interesting to notice that a rough extrapolation of the 3 data points (full triangles) in Fig.7 towards lower impact parameters would lead to a value which is close to the threshold energy E_{RAD} (dashed area) of the radial flow extracted [5,35] from central collision studies ($b \leq 2fm$). On the other hand, a very similar behaviour is observed for the balance energy (open circles in Fig.7). Here one can note again that the values of E_{TRA} are larger than those of E_{BAL} in the whole explored impact parameter domain.

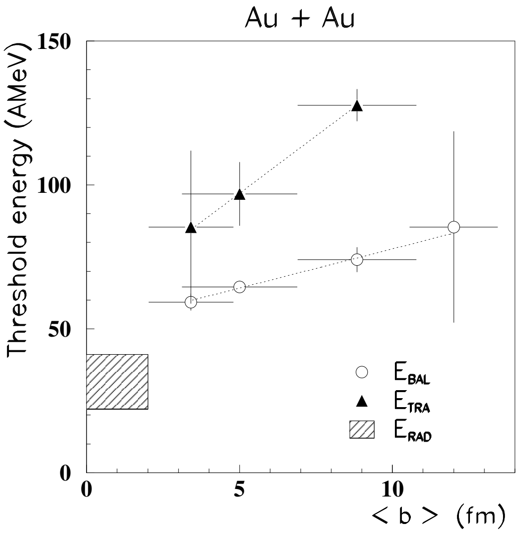

Figure 7: Threshold energies E_{BAL} and E_{TRA} as a function of the mean impact parameter $< b >$. The mean impact parameter values are extracted with the IQMD model (the corresponding RMS deviations are indicated by the horizontal bars). Error bars correspond to statistical uncertainties only. The dotted lines are linear fits to the data. The hatched area indicates the threshold energy of the radial flow [5,35] estimated in highly central collisions ($b \leq 2fm$).

It is still premature to go to more quantitative interpretations of these data because of the large experimental uncertainties. In addition, the fact that E_{BAL}, E_{TRA} and E_{RAD} are extracted from different observables makes difficult their direct comparison. Nevertheless, it is tempting to speculate on the basis of the observations in Fig.7 on a common phenomenon at the origin of all different forms of collective flow (sideward, squeeze-out, and the radial flow), which takes place for the same deposited energy : when nuclear matter is heated above a certain limit, the coercive nuclear forces are counterbalanced by the thermal pressure and the system starts to expand above this threshold where the overall force becomes repulsive. This expansion of nuclear matter takes an azimuthally symmetric pattern (radial flow) in highly central collisions. While in semi-central collisions the expanding matter is pushed to the side (sideward flow) and the presence of cold spectator remnants hinders participant nucleons from escaping in the reaction plane, which gives rise to a preferential out-of-plane emission (squeeze-out). This scenario for the squeeze-out effect is somewhat consistent with the observed correlation between the anisotropy ratio and the impact parameter (Fig.5). It is worth noting that the incident energy where the radial flow sets in corresponds to an available c.m. energy of $8.75A\ MeV$ [35] which is close to the one of the caloric curve [36], reported by the ALADIN group, where the temperature grows again after the plateau.

7 Conclusions

A systematic study of Au + Au collisions at several incident energies going from 100 to $800A\ MeV$ was carried out using the phase I setup of the FOPI apparatus at GSI-Darmstadt. Several observables related to different forms of nuclear matter flow in semi-central collisions were investigated. We reported here on some of the most relevant experimental results concerning : i) the flow of intermediate mass fragments ii) the centrality dependence of collective observables and iii) the onset of nuclear matter expansion.

The flow parameter was found to exhibit an increase with the size of the detected particle which turns into saturation for the heavier fragments. A very similar trend was also observed for the squeeze-out effect. This dependence on the fragment size can be understood in the framework of a simple picture of an expanding thermal source where particles of different masses share the same thermal energy but their collective energy is proportional to their mass. The relevance of IMF flow measurements as a probe of the stiffness of the nuclear equation of state was illustrated through detailed comparisons to the predictions of the IQMD model. The latter reproduces quite well the sideward flow data, but it underpredicts significantly the experimental multiplicities of IMF.

By combining both PMUL and ERAT observables, it was possible to investigate the centrality dependence of the directed transverse flow p_x^{dir} over a broad range of impact parameters (1 to $10fm$). We found that the correlation between p_x^{dir} and the impact parameter shows the expected behaviour with a well pronounced maximum at intermediate b values (around $3.5fm$) and vanishing sideflow at both the low and high b ends. This behaviour is qualitatively well reproduced by the IQMD model. More detailed comparisons should contribute to constrain separately both EoS and momentum dependent interaction effects. On the other hand, the correlation between the squeeze-out ratio R_N and the impact parameter was found to exhibit a similar bell-shaped behaviour with a maximum close to $b = 6fm$. This trend, observed at $E/A \geq 250\ MeV$, is consistent with an expansion-shadowing picture. At lower incident energies a clear change in the emission pattern, from a preferential in-plane emission at large b values to an enhanced out-of-plane emission at low b values, was observed.

The onset of nuclear matter flow was investigated by extrapolating the measured excitation functions for both sideward and squeeze-out flow effects. Both balance and transition energies were found to be independent of the size of the detected fragment. The value extracted for E_{TRA} is larger than the one obtained for E_{BAL}, which might indicate that at the balance point the compression is not high enough to generate an enhanced out-of-plane emission. This is in qualitative agreement with recent theoretical predictions in the framework of the QMD model [33]. A clear impact parameter dependence of both balance and transition energies was evidenced. The results are consistent with the threshold energy of the radial flow estimated from central collision studies. The relevant parameter seems to be the energy to be deposited into the system in order to overcome the attractive nuclear forces.

Further quantitative interpretations of the present experimental data in the framework of dynamical transport models should provide deeper insight into the basic properties of highly excited and compressed nuclear matter, an essential step towards an unambiguous determination of the nuclear matter equation of state.

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