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SQUEEZE-OUT OF NUCLEAR MATTER IN Au (100 to 800 *A*MeV) + Au COLLISIONS

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C. ROY, L. TIZNITI, P. WAGNER
and the *FOPI* Collaboration

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Abstract : *Azimuthal distributions of mid-rapidity light charged particles and intermediate mass fragments emitted in Au+Au collisions at incident energies ranging from 100 to 800 AMeV have been measured using the FOPI apparatus at GSI, Darmstadt. The magnitude of the anisotropy signal is found to increase with the fragment charge and seems to flatten off above $Z = 4$. At high incident energies, the correlation between the anisotropy ratio and the collision centrality exhibits a maximum at intermediate impact parameters, supporting an expansion-shadowing scenario. At low incident energies, a signature for a transition from an enhanced in-plane emission pattern to a preferential out-of-plane emission is evidenced. It is shown that this transition takes place at an impact parameter close to 6 fm for a bombarding energy of 100AMeV.*

Introduction

The emission of mid-rapidity particles offers the possibility to probe the properties of highly compressed and heated nuclear matter, created during the early stages of high energy heavy ion collisions, in the overlap region between the colliding nuclei. Particles emitted in the direction perpendicular to the reaction plane are, in this regard, particularly interesting as they are not affected by the influence of the surrounding cold spectator remnants.

The preferential emission of nuclear matter out of the reaction plane (i.e. squeeze-out) was predicted by hydrodynamical calculations [1] and experimentally evidenced [2, 3] from the measurements of azimuthal distributions of light charged particles at incident energies of a few hundreds of MeV/nucleon. These studies have been recently extended to neutrons [4, 5] and pions [6, 7, 8]. The relevance of the out-of-plane anisotropy for the study of the nuclear equation of state was established from microscopic transport calculations [9, 10]. It was shown that the magnitude of the anisotropy signal carried out by high transverse momentum particles is more sensitive to the stiffness of the equation of state than the sideward transverse flow observable.

On the other hand, at lower incident energies a transition from preferential in-plane emission pattern to an enhanced out-of-plane emission was reported in recent studies [11, 12]. This transition may be attributed to a change from a collective rotational behaviour governed by the attractive mean field at low energies, to the high energy squeeze-out effect resulting from the repulsive pressure built up during the high density stage of the collision. The incident energy where this transition sets in is a very promising observable to examine the influence of the in-medium nucleon-nucleon cross sections [12], providing an additional constraint on another basic parameter in the dynamical models.

In this contribution, we report new experimental results obtained with the FOPI detector [13] at SIS/GSI (Darmstadt), for Au+Au collisions at bombarding energies going from 100 to 800AMeV. This broad energy range allows both transition phenomenon and high energy squeeze-out effects to be simultaneously investigated. Our present study also includes the first measurements of azimuthal anisotropies of intermediate mass fragments (IMF, $3 \leqslant Z \leqslant 15$). The latter are expected to show stronger sensitivities to collective effects due to their relatively low unordered thermal velocities. The inclusion of the relative contributions of IMF allows coalescence invariant anisotropy observables to be reconstructed, which is important in the study of impact parameter and beam energy

dependence of the anisotropy signal. This facilitates also direct comparisons to dynamical model predictions. The data are presented over a large impact parameter range (from $\simeq 3$ to $\simeq 10fm$) in order to explore in detail the correlation of the azimuthal anisotropy with the collision centrality. Influences of fluctuations of the reaction plane, on the one hand, and the directed sideward flow, on the other hand, are examined in order to avoid possible ambiguities in the interpretations of the trends observed in the data.

1 Experimental procedure

The experimental data presented in this contribution concern the Au + Au system at 6 incident energies E_{lab} = 100, 150, 250, 400, 600 and 800 AMeV. 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 [13] consists of a highly segmented Forward Wall covering in full azimuth the laboratory polar angles between 1.2° 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 negligeable multi-hit rate. The apparatus ensures a very good azimuthal symmetry, an important feature for the reconstruction of the reaction plane and azimuthal distributions measurements. A more detailed description of the different components of the FOPI apparatus can be found in ref. [13].

2 Event characterization

The study of out-of-plane azimuthal anisotropy requires a good event characterisation both in impact parameter and azimuthal orientation of the reaction plane. Moreover, in order to avoid ambiguities in the interpretation of the data due to the influence of the in-plane transverse flow, the anisotropy signal must be determined around the flow axis.

2.1 Impact parameter selection

To sort out the measured events according to their degree of centrality, we have employed the standard method based on the correlation between the multiplicity of emitted particles and the impact parameter. Simulation studies allowed us [14] to show that with the FOPI phase I setup this criterium, as compared to others, provides the best scaling for exploring the impact parameter dependence of flow observables.

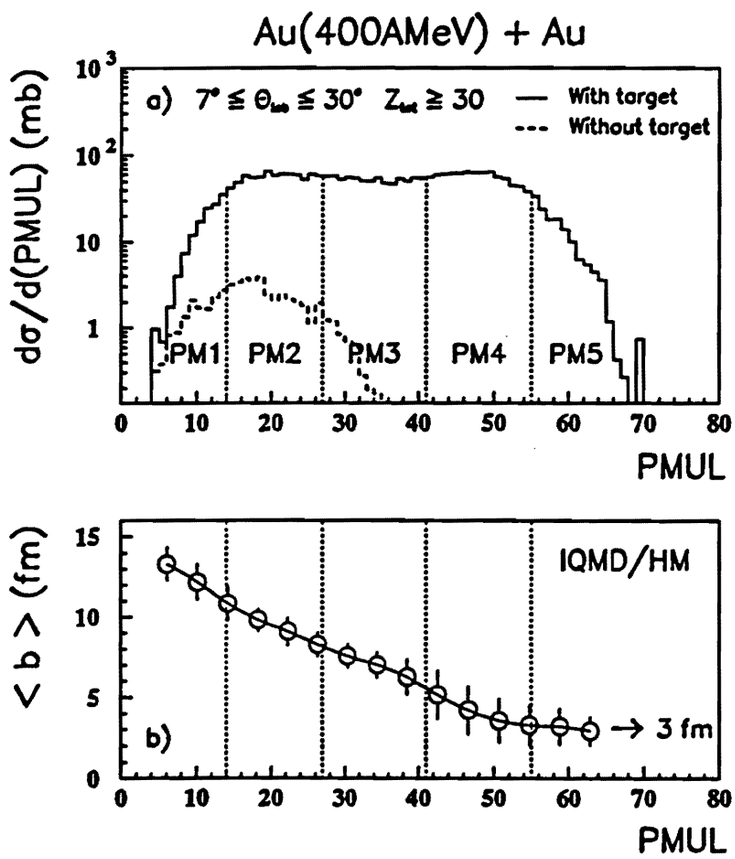

Figure 1 : *(a) Multiplicity distribution of charged particles detected in the Plastic Wall ($7° \leqslant \Theta_{lab} \leqslant 30°$) at an incident energy of 400AMeV. The background contribution is indicated by the dashed histrogram (without target). The different event classes PM1 - PM5 are indicated by the vertical lines. The distributions are obtained by requiring a total detected charge in the forward c.m. hemisphere larger than 30. (b) Correlation between the charged particle multiplicity and the mean impact parameter simulated with the IQMD model including the detector filter. The error bars indicate the RMS extension of the distributions.*

An example of a charged particle multiplicity distribution measured in the polar angular range $7° \leqslant \theta_{lab} \leqslant 30°$ at 400AMeV is displayed in Fig.1.a (solid histogram). It has been obtained after background substraction by comparing the measurements with and without target. This distribution exhibits the typical flat plateau followed by a steep decrease at high multiplicities. The highest multiplicity bin (labelled PM5) has been defined by cutting at half of the plateau value corresponding to about 5% of the total reaction cross section. The remaining part of the distribution has been subdivided into four equally spaced bins, according the procedure used by the Plastic Ball collaboration [15]. Only events belonging the PM2 - PM5 region which are very little affected by the background contribution, were considered in the analysis.

Fig.1.b shows the correlation between the charged particle multiplicity and the impact parameter at an incident energy of 400AMeV, obtained from Isospin Quantum Molecular Dynamics (IQMD) model [16] simulations taking into account the detector filter. As it can be seen, the multiplicity selection criterium allows the coverage of a large impact parameter range ($3fm \leqslant < b > \leqslant 10fm$) including the region of semi-peripheral collisions. This is useful for the study of the squeeze-out effect as its correlation with the impact parameter is predicted to show a maximum at intermediate (close to $7fm$) impact parameters [17]. The b selection plays also an important role in the study of the onset of the flow as we will see in section 3 in the case of the so-called transition energy. In this regard, a heavy system such as Au+Au is well suited as the impact parameter can be determined with a better accuracy than for lighter systems.

2.2 Reaction plane reconstruction

To estimate the azimuth of the reaction plane, we have used the well known transverse momentum analysis (TMA) method devised by Danielewicz and Odyniec [18]. In the framework of this method, the reaction plane is determined by the vector $\vec{Q}$ reconstructed for each event from the transverse momenta $\vec{p_\nu^t}$ of all detected particles : $\vec{Q} = \sum_{i=1}^{M} \omega_\nu \vec{p_\nu^t}$ where M is the multiplicity of the event and $\omega_\nu = 1$ if $y^{(0)} > \delta, -1$ if $y^{(0)} < \delta$ and 0 otherwise ($y^{(0)}$ is the particle rapidity divided by the projectile rapidity, in the center of mass system). The parameter δ is choosen equal to 0.25.

The dispersion of the reconstructed plane, due to a finite number of particles, is estimated [18] by subdividing randomly each event into two and determining the difference in azimuth ($\Delta\varphi$) between the reaction planes extracted from the two sub-events. The

results, expressed in terms of the width $\sigma(\Delta\varphi)$, are presented in Fig.2 (full circles) at E_{lab} = 400AMeV. They are quite well reproduced by filtered IQMD calculations (open crosses in Fig.2) where the simulated events were treated in the same way as for the data. The slight difference between data and IQMD points is due to the fact that the model overestimates the charged particle multiplicity. To examine the reliability of the method used to estimate the dispersion on the reaction plane, we show also in Fig.2 (full triangles) the results of filtered IQMD simulations where $\sigma(\Delta\varphi)$ is evaluated as the deviation of the reconstructed reaction plane from the true one (known in the model). From the comparison of both sets of IQMD points, one can see that for semi-central collisions (PMUL/PM5$_L$ $\geqslant$ 0.5) the dispersion of the reconstructed plane can be reasonably estimated in the data, while for more peripheral collisions, where the number of emitted particles is relatively low, the estimate of $\sigma(\Delta\varphi)$ in the data is dubious. In this case, corrections of the experimental observables for fluctuations of the reaction plane could be done only on the basis of a theoretical model.

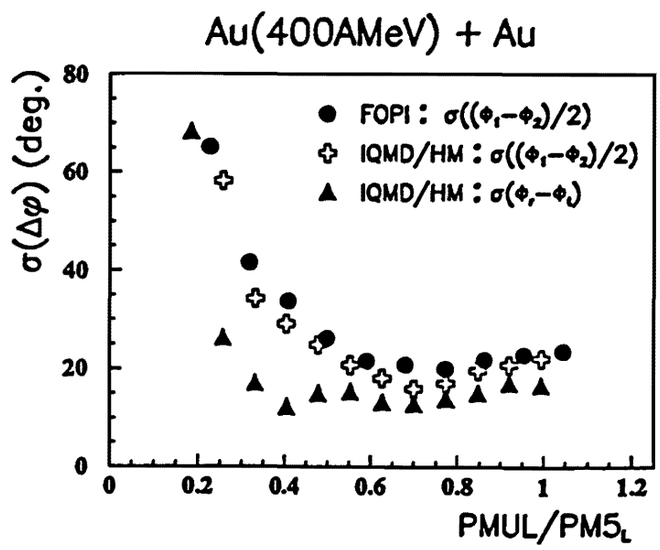

Figure 2 : *Accuracy ($\sigma(\Delta\varphi)$) on the reconstructed reaction plane for Au(400AMeV)+Au as a function of the reduced charged particle multiplicity PMUL/PM5$_L$ (PM5$_L$ is the lower limit of the PM5 event class). The data correspond to the full circles. The results of IQMD simulations obtained by applying the same method as for data are represented by the crosses. The full triangles indicate the results of IQMD simulations obtained for the azimuthal deviation of the reconstructed plane (Φ_r) from the true one (Φ_t).*

The influences of these effects on the observed trends of the squeeze-out signal, in particular as a function of the collision centrality, will be discussed in the next section.

3 Experimental results and discussion

Azimuthal distributions $dN/d\varphi$ ($\varphi = \Phi - \Phi_R$) around the beam axis of mid-rapidity particles, selected by imposing a rapidity cutoff $-0.15 < y^{(0)} < 0.15$, were extracted at different bombarding energies and for different multiplicity bins. To avoid autocorrelation effects, the azimuthal orientation of the reaction plane (Φ_R) was reconstructed for each particle by including all detected particles belonging to the same event except the one being considered.

Fig.3 shows typical examples of $dN/d\varphi$ distributions measured at an incident energy of 600 AMeV for the semi-central PM4 event class. These distributions were obtained for mid-rapidity particles (Z = 1, 2 and 3) emitted with normalised transverse momenta ($p_t{}^{(0)} = (p_t/A)/(p^{cm}_{proj}/A_{proj})$) comprised between 0.06 and 0.55. This condition was introduced in order to avoid distorsions due to geometrical limits of the detector ($1.2° \leqslant \theta_{lab} \leqslant 30°$). It is worth mentionning that even by doing so, the distributions (Fig.3) still exhibit some asymmetries which can be attributed [19] to complex detector biases (inefficiences, double-hits, etc.) and to some extent to momentum conservation effects.

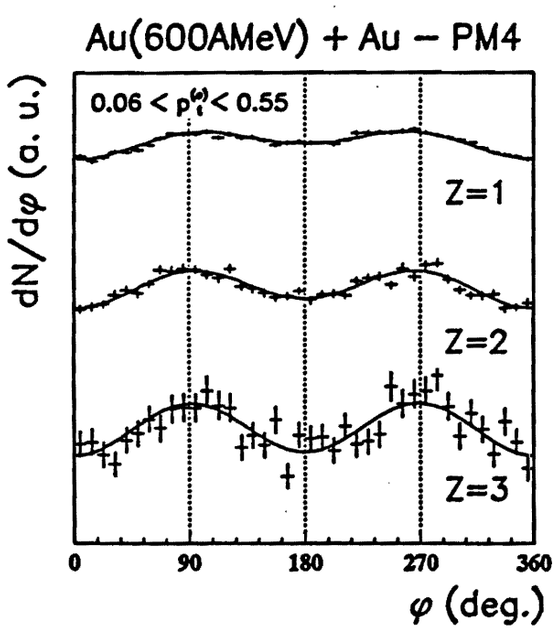

Figure 3 : *Typical examples of azimuthal distributions of mid-rapidity ($-0.15 \leqslant y^{(0)} \leqslant 0.15$) particles measured in semi-central Au+Au collisions at 600 AMeV. $\varphi = \Phi - \Phi_R$ is the azimuthal angle around the beam axis with respect to the reaction plane. The distributions are extracted with a transverse momentum cut $0.06 < p_t^{(0)} < 0.55$. The curves are second order polynomial fits to the data (see text). Error bars correspond to statistical uncertainties.*

A clear preferential emission is observed in the direction perpendicular to the reaction plane (φ = 90° and 270°). This enhanced emission becomes progressively more pronounced as the size of the detected fragment increases, which reflects the stronger sensitivity of IMF to collective effects. Similar anisotropies are also observed for the mean

transverse kinetic energy [20], indicating that not only more particles are ejected in the out-of-plane direction but that those particles are also more energetic.

In order to examine the data in a more quantitative way, we have extracted the magnitude of the squeeze-out signal (R_N) as the ratio of the number of particles emitted perpendicular to the reaction plane to the number of particles emitted in the reaction plane : $R_N = (N(90°) + N(270°)) / (N(0°) + N(180°))$. This has been done by fitting a function of the form $N(\varphi) = a_0 + a_1 cos(\varphi) + a_2 cos(2\varphi)$ to the data (curves in Fig.3).

The R_N values obtained at 250AMeV are presented in Fig.4 as a function of the charge of the detected fragment. The observed trend seems to be similar to the one characterizing the sideward flow [14, 20, 21] : R_N increases significantly from $Z = 1$ to $Z = 3$ and flattens-off for heavier fragments ($Z \geqslant 4$). This behaviour supports the fact that IMF provide a good probe for the collision dynamics and collective effects, while light particles are more affected by the unordered thermal motion. It can be understood [14] from a simple picture of an anisotropically expanding thermal source where particles with different masses share the same thermal energy but their collective energy is proportional to their mass. It is also interesting to mention that recent microscopic transport calculations using the IQMD code predict a similar trend [9].

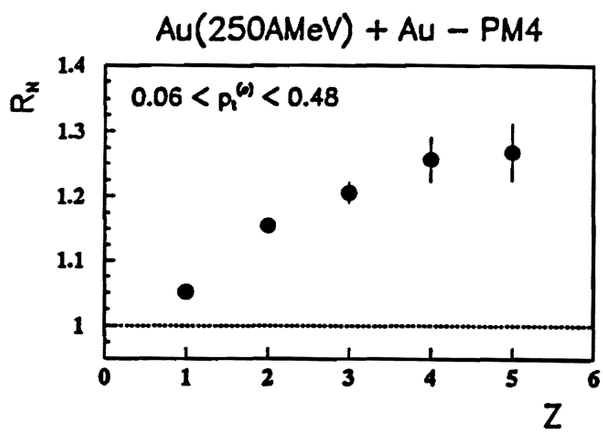

Figure 4 : *Magnitude of the squeeze-out signal (R_N) versus the charge of the detected fragment for PM4 events at an incident energy of 250AMeV. Error bars include statistical errors only.*

The present results confirm the important role of IMF in the study of collective effects. On the other hand, it was shown [21] that in the beam energy range under investigation in the present work, a substantial fraction of the nuclear matter emerging from the collision is emitted in the form of IMF. This fraction depends on the bombarding energy and the collision centrality. At 150AMeV, about 30% of the total detected charge for the PM5 event class is identified as IMF. These considerations illustrates the need of incorporating IMF into the anisotropy signal R_N.

The results reported in what follows include the contributions of all detected particles each weighted by its charge. By doing so, we reconstruct coalescence invariant anisotropy quantities, which makes meaningful the investigation of the effect as a function of the impact parameter and the beam energy dependence. This makes also possible comparisons of data to theoretical predictions even if the model used underestimates IMF multiplicities, or does not incorporate IMF production.

As it can be seen in Fig.5 at 400AMeV, the anisotropy effect is more pronounced for high p_t particles than for low p_t particles. This is in qualitative agreement with IQMD predictions [9, 10], which show moreover that the sensitivity of the anisotropy signal to the stiffness of the equation of state increases with the transverse momentum of emitted particles. Therefore, in order to extract relevant information from the data, we determined the anisotropy signal for high p_t particles by imposing a p_t cut whose limits were dictated by acceptance and statistics considerations [14].

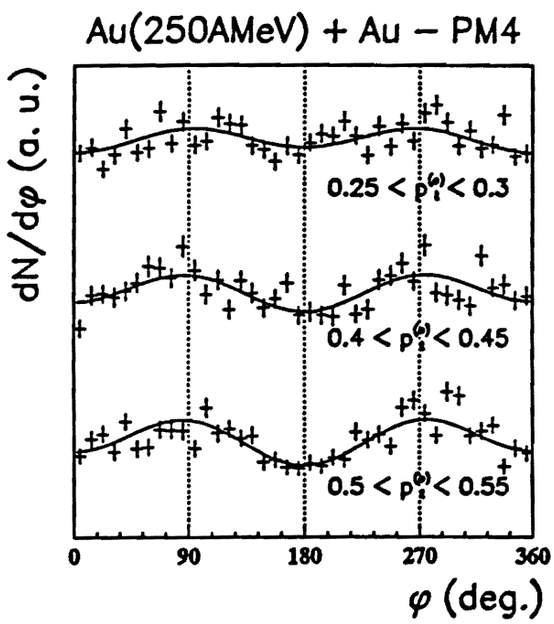

Figure 5 : *Azimuthal distributions of mid-rapidity particles measured in semi-central (PM4 class) Au + Au collisions at 250 AMeV, under different p_t cuts : $0.25 < p_t^{(0)} < 0.3$, $0.4 < p_t^{(0)} < 0.45$ and $0.50 < p_t^{(0)} < 0.55$. The curves are second order polynomial fits to the data. Error bars correspond to statistical uncertainties.*

The dependence of the the anisotropy signal R_N on the collision impact parameter is presented in Fig.6 at 4 incident energies going from 100 to 400AMeV. The ratios R_N were extracted from the azimuthal distributions around the beam axis of mid-rapidity particles with $0.40 < p_t^{(0)} < 0.55$. It is worth noting that the results at 100AMeV were obtained by excluding particles emitted in the backward c.m. hemisphere in order to avoid possible distorsions due to threshold effects. The impact parameter b_g was estimated from the measured cross sections by assuming a sharp-cut-off approximation.

The use of the impact parameter allows us to perform direct comparisons of data measured at different bombarding energies.

The observed correlation between the ratio R_N and the impact parameter exhibits a very different trend when the incident energy rises from 100 to 400AMeV. At the lowest bombarding energy (100AMeV), a clear change in the emission pattern is evidenced : with decreasing impact parameter, one observes a transition from a preferential in-plane azimuthal distributions to the squeeze-out effect characterized by an enhanced out-of-plane emission. 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 $6fm$). It should be mentioned that the results obtained at higher energies (600 and 800AMeV) are quite similar to those observed at 400AMeV.

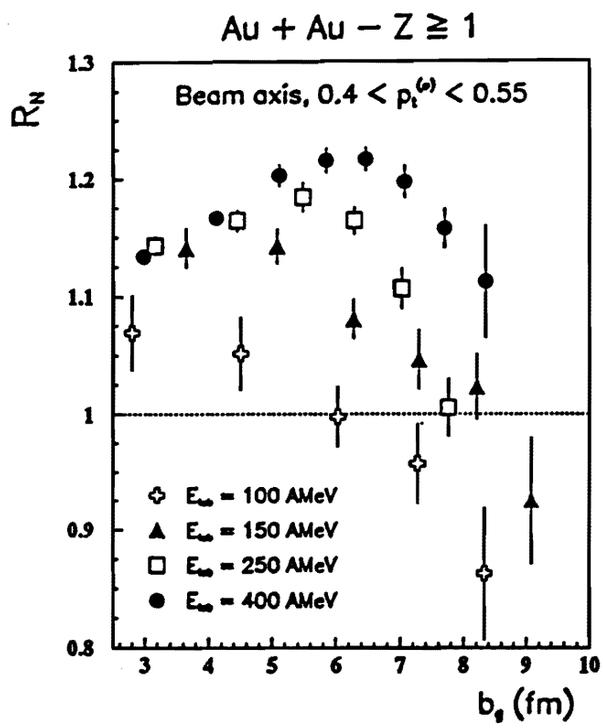

Figure 6 : *Anisotropy ratio R_N as a function of the impact parameter b_g, for Au+Au collisions at different bombarding energies. The signal is determined around the beam axis with the $p_t^{(0)}$ cut indicated in the figure. Error bars correspond to statistical uncertainties only.*

As already stated in the introduction, there are two effects which might influence the R_N ratios : i) the dispersion of the reconstructed reaction plane with respect to the true one, which tends to bias down the magnitude of the signal and ii) the in-plane transverse flow which favours the emission of particles in the reaction plane. In both cases, the magnitude of the effect is impact parameter dependent. Therefore, in order to eliminate possible ambiguities in the interpretation of the experimental observations in Fig.6, it was necessary to examine the respective influences of these effects on the correlation between the anisotropy ratio and the impact parameter.

Fig.7 and 8 show that the bell-like shape of the distributions observed at high beam energy, is preserved after taking into account both above mentioned effects. Corrections for the inaccuracy on the reconstructed reaction plane [14] lead to higher values of the anisotropy ratio, but the overall trend remains the same (Fig.7). On the other hand, the determination of the signal around the flow axis (Fig.8) instead of the beam axis does not affect the general shape of the distribution, although one observes a slight shift of the maximum towards lower impact parameters. This shift is due to the fact that the influence of the in-plane side-splash flow increases with decreasing impact parameters. To obtain the ratios R_N around the flow axis, we rotated the events belonging to each centrality bin by the corresponding average flow angle. The latter was estimated from the measurements of IMF sideward flow [14, 22].

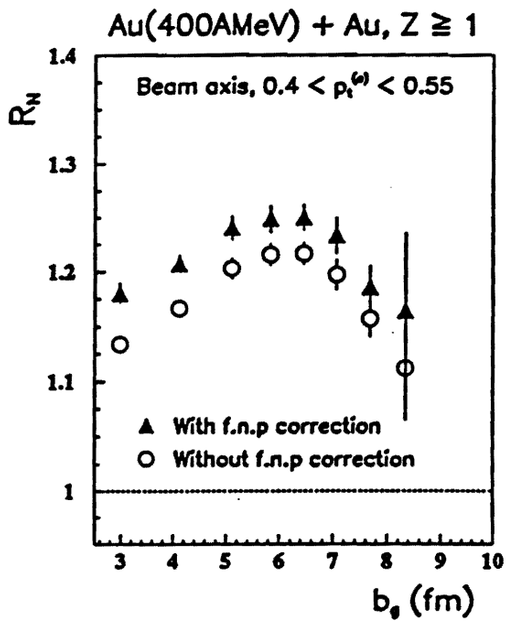

Figure 7 : *Anisotropy ratio R_N as a function of the impact parameter b_g, for Au+Au collisions at 400AMeV. The signal is determined around the beam axis with the $p_t^{(0)}$ cut indicated in the figure. Error bars correspond to statistical uncertainties only. The results are shown with (full triangles) and without (open circles) corrections for the uncertainty on the reconstructed reaction plane.*

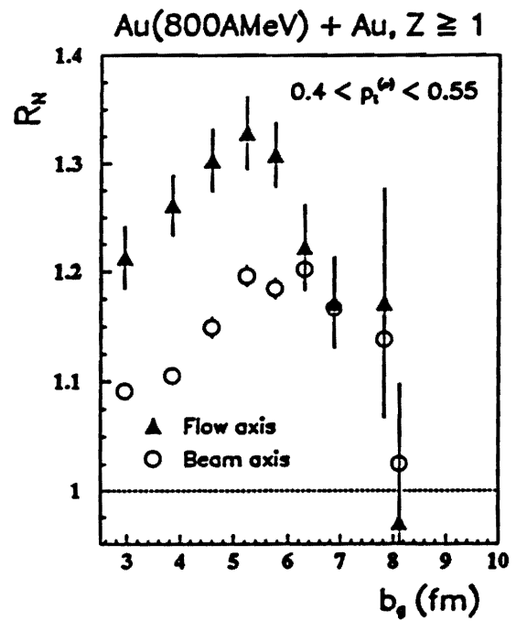

Figure 8 : *Anisotropy ratio R_N as a function of the impact parameter b_g, for Au+Au collisions at 800AMeV. The signal is determined with the $p_t^{(0)}$ cut indicated in the figure. Error bars correspond to statistical uncertainties only. The results are shown around the flow axis (full triangles) and the beam axis (open circles).*

The transition from $R_N > 1$ to $R_N < 1$ observed at $E_{lab} = 100$AMeV cannot be caused by any of these two effects. Indeed, fluctuations of the reaction plane tend to attenuate an anisotropy signal regardless of whether the ratio R_N is larger or smaller than 1. An extraction of the anisotropy ratio around the flow axis would shift up the experimental points (open crosses in Fig.6). However, $E_{lab} = 100$AMeV is close to the threshold energy of the sideward flow [14], so that the flow angle is expected to be fairly low in particular at large b_g's where the in-plane anisotropy is observed.

Let us now go back to the interpretation of the experimental observations of Fig.6. At high energies, the maximum observed near $b_g = 6fm$ 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 noticing that recent IQMD caculations for neutrons [17] predict a similar bell-shaped correlation with a maximum around $7fm$.

At low incident energies ($E_{lab} \leqslant 150$AMeV), clear evidence for a transition from an enhanced in-plane emission pattern ($R_N < 1$) to a preferential out-of-plane emission ($R_N > 1$) is observed. The results show that this transition takes place close to E_{lab} = 100AMeV for collisions with impact parameters $b_g \simeq 6fm$. This effect was already observed for a lighter Zn+Ni at GANIL [11]. It is worth mentionning also that our results are qualitatively consistent with data reported very recently by Tsang et al. [12] for the same system Au+Au. This transition might be attributed to a change from a collective rotational behaviour governed by the attractive mean field at low energies, to the high energy squeeze-out effect resulting from the repulsive pressure built up during the high density stage of the collision.

Another way to investigate this transition phenomenon is to look at the excitation function of the R_N ratio, which is presented in Fig.9 for $Z = 2$ and 3 particles emitted in semi-central collisions (PM4 bin). The incident energy dependence of the signal is qualitatively consistent with the earlier results of the Plastic ball collaboration [23] : R_N reachs a maximum at incident energies near 400AMeV. The reduction of the squeeze-out observed at the highest energies might indicate that a smaller fraction of the available energy is converted into the collective degrees of freedom. On the other hand, the behaviour of the signal at the lowest energies suggests the transition from out-of-plane to in-plane enhancement when the bombarding energy decreases.

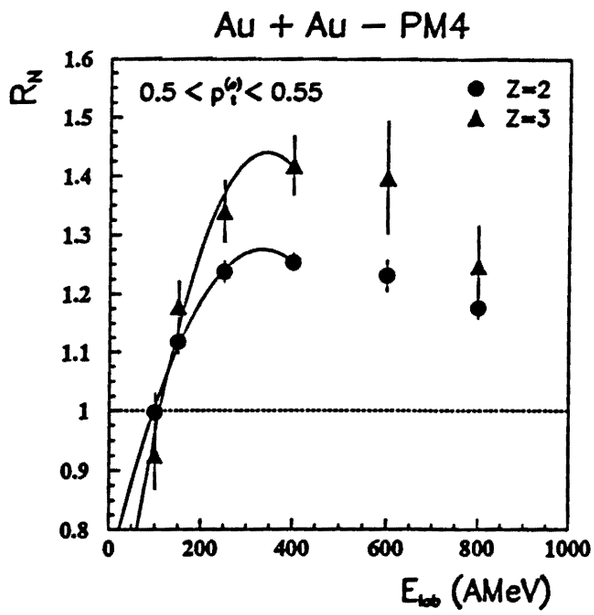

Figure 9 : *Excitation function of the R_N ratio for Z =2 (circles) and 3 (triangles) particles emitted in semi-central collisions (PM4 bin). The signal is determined with the $p_t^{(0)}$ cut indicated in the figure. Error bars correspond to statistical uncertainties only. The curves represent the results of a fit with a second order polynomial function.*

In order to extract the incident energy where this transition takes place (E_{tra}), we have adjusted the experimental points with a second order polynomial function (curves in Fig.9). The intercept of $R_N = 1$ with the curves gives an estimation of the transition energy E_{tra}. It is found that E_{tra} is located near 100AMeV almost independently of the size of the detected fragment. This transition energy is larger than the balance energy $E_{bal} \simeq$ 65AMeV characterising the disappearence of the sideward flow for the same event class [14]. This result, which is in qualitative agreement with IQMD calculations for the Ca+Ca system [24], seems to indicate that the compression reached at the balance point is not high enough to produce the out-of-plane emission of nuclear matter.

Comparisons of these data to dynamical model predictions should provide interesting information on the in-medium nucleon-nucleon cross sections [12, 25].

Conclusions

A systematic study of the out-of-plane emission of nuclear matter in Au(100-800AMeV)+Au collisions has been achieved using the phase I of the FOPI detector at GSI. The squeeze-out signal was extracted from azimuthal distributions with respect to the reaction plane, of mid-rapidity light charged particles and IMF.

The results show that the out-of-plane emission increases with the fragment charge and flattens-off for the heaviest fragments. This trend, which is similar to the one

characterizing the sideward flow, agrees with a picture of an expanding thermal source where a collective motion is superimposed on the thermal one. The centrality dependence of the squeeze-out has been studied in a high p_t cut in order to extract relevant information from the data, and including the contribution of all detected particles. We have found that the behaviour of the R_N ratio with the reaction centrality changes with the incident energy. At high incident energy, the squeeze-out signal exhibits a bell-shape with a maximum at intermediate impact parameters. This trend is consistent with an expansion-shadowing scenario, where the expansion of the highly compressed participant nuclear matter is hindered by the presence of cold spectator remnants. At low energy (100AMeV), the data show clearly a transition from in-plane to out-of-plane emission when the impact parameter decreases. This phenomenon might be explained as a change from a collective rotational motion for large impact parameters to the squeeze-out effect for smaller impact parameters. The transition energy extracted from the data for semi-central events is found to be higher than the corresponding balance energy, which might indicate that the compression is not high enough at the balance to generate the out-of-plane enhancement.

This analysis will be extended in the near future, to the data obtained with the complete FOPI detector, from Au+Au, Ni+Ni and Xe+CsI measurements for incident energies ranging from 90 to 400AMeV.

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