CLUSTERS AS SENSITIVE PROBES FOR A DEEPER UNDERSTANDING OF BARYON FLOW OBSERVABLES

M. PETROVICI
National Institute for Physics and Nuclear Engineering,
P.O. - MG6, 76900 Bucharest, ROMANIA
E-mail: mpetro@ifin.nipne.ro

FOPI COLLABORATION

Details on the azimuthal- and polar angle- dependence of the flow phenomena in semi-central and respectively central heavy ion collisions, using reaction products composed of few nucleons, are presented.

1 Introduction

As the first predictions on heavy ion collisions at relativistic energies have been based on hydrodynamical models it is obvious that part of the terminology has been adopted from hydrodynamics. This is the case also with the flow term. In this contribution we will concentrate on some aspects related to the flow in terms of correlated or ordered motion in which many particles are involved. In the moving frame the particles are not in rest, usually being characterized by a thermal motion. Concequently the associated thermal velocities are smaller for heavier objects. This is the most obvious argument which recommends the clusters as cleaner probes for detailed quantitative estimates on any type of flow.

The collective expansion of hot and dense nucler matter produced in heavy ion central collisions is well confirmed by now. The mass dependence of the fragments kinetic energy and their abundancy give strong support for the existence of an important collective expansion which cools down the disassembling matter so that heavy clusters can be produced. Although the central collisions appear to deliver the cleanest signal on the collective expansion, two aspects are worth to be mentioned: i) if the axial symmetry for such geometry holds, the spherical one has to be carefully studied, preequilibrium emission and tranparency effects influence the conclusion on the spheroidal shape of the expanding object, ii) the nuclear matter can escape freely in any direction perpendicular to the collision axis starting from the very first moments of the collision. The confinement is realized only by the remaining regions of the nuclei not yet entered in the reaction zone along the collision axis.

At lower centrality one has to deal with the complicated situation of rotating expanding objects in the presence of the spectator matter. However, there are some advantages of such studies: i) rotation and shadowing can be used as internal clocks for deeper information on the expansion dynamics, ii) the centrality can be used to control the shape and content of the fireball and shadowing matter, iii) for a given centrality the passage time of the shadowing objects can be controled varying the incident energy, iv) the confinement of the fireball by the spectators is more compact in the reaction plane.

Based on symmetry arguments these two type of phenomena are called azimuthaly symmetric and elliptic flows, respectively.

Systematic studies of different aspects of flow evidenced in the first experiments on relativistic heavy ion collisions performed with Phase I of the FOPI detector at GSI Darmstadt [1] have been followed in a series of experiments on Ni+Ni, Xe+CsI and Au+Au at energies between 90 and 400 A·MeV with complete configuration of the FOPI setup. The results presented here are based on this set of data. Details on the experimental configuration and analysis technique can be found elsewhere [2,3,4,5,6].

Section 2 is dedicated to the results of a multidimensional analysis of the incident energy where a transition from in-plane to out-of-plane azimuthal enhancement takes place, as a function of the mass of emitted particles, their transverse momentum and collision geometry. The excitation functions of the mean kinetic energy, flow and temperature for Z=2 reaction products in- and out-off-reaction plane for mid central collisions, are presented in Section 3. The polar angle- and A_{part}-dependence of the azimuthally symmetric correlated motion in highly central collisions is the subject of Section 4. The conclusions are presented in Section 5.

1.1 Transition from in-plane to out-of-plane emission for mid-central heavy ion collisions

Almost a decade ago, two types of azimuthal anisotropies have been evidenced in mid-central heavy ion collisions [7,9,10,11]. Following their shape relative to the reaction plane and the main mechanism behind them they have been baptized as in-plane and out-of-plane enhancement or rotational-like [7] and squeeze-out [8,9,10,11] phenomena, respectively. How the transition from one to the other scenario takes place as a function of incident energy, for different collision geometries and type of the reaction products was a question addressed few years later for light [12] and heavy [13,14,15,5,16,17,6] systems. Relative to the Phase I FOPI studies [13,16,17], the present data make possible the azimuthal distribution studies in the rotated reference frame, with no limitation on transverse momentum and as a function of mass of light charged reaction products. The procedure used to extract the transition energy (E_{tran}) can be followed in Fig.1. For a given centrality range, transverse momentum and mass of the analyzed reaction products, the squeeze-out ratio - R_N=(1-a_2)/(1+a_2) (a_2 being the second coefficient of a Fourier expansion in azimuth), is represented as a function of incident energy (E_{inc}).

Squeeze-out signal corresponds to $R_N > 1$ while in-plane enhancement of the azimuthal distribution is characterized by $R_N < 1$. The continuous lines correspond to the result of fits using a polinomial function. The intersections of these lines with the one corresponding to R_N = 1 value are defined as E_{tran}. Fig.1 shows a clear mass dependence of the transition energy, lower values corresponding to heavier fragments for a given centrality and a given range in the scaled transverse momentum $p_t^{(0)} = (p_t/A)/(p_P^{cm}/A_P)$.

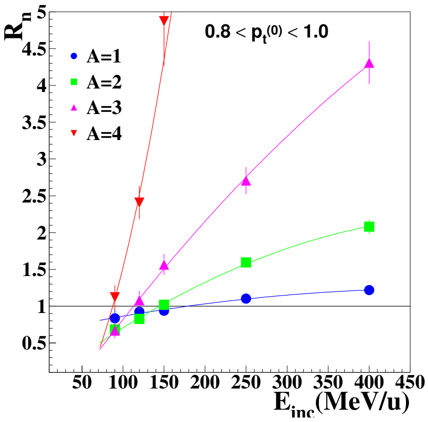

Figure 1. Squeeze-out ratio as a function of incident energies for Au + Au, CM3 centrality and A=1,2,3 and 4.

For a rotating emitting source one would expect a larger in-plane alignment for heavier fragments [14]. This effect alone can not explain the mass dependence of E_{tran}. Therefore a dynamical effect has to be considered besides the pure geometrical one of shadowing. Following the same recipe for different regions of $p_t^{(0)}$, a two dimensional dependence of the E_{tran} values as function of mass of the analyzed reaction products and transverse momentum can be obtained. The result is represented in Fig.2. A continuous decrease of the E_{tran} as a function of $p_t^{(0)}$ is evidenced for all analyzed particles and the difference in E_{tran} values for different particles is decreasing towards larger values of $p_t^{(0)}$. At large $p_t^{(0)}$ the contribution comes from larger expansion velocities, earlier expansion phase of the fireball [18,4], higher shadowing. At lower values of $p_t^{(0)}$, the expansion zones are less localized specially for light fragments due to larger contribution of the thermal velocities relative to the collective ones, the shadowing being less effective on the in-plane yields. These studies can be done for different centralities. The result of such analysis is represented in Fig.3 for Z=1,2 and 3 integrating on $p_t^{(0)}$. The shown centrality bins, ER5, ER4, CM3 and CM2, correspond in a geometrical "sharp cut-off" approximation to the impact parameter intervals 0-2, 2-4, 4-6 and 6-8 fm, respectively. At lower impact parameters the amount of energy which can be transferred in a rotational-like motion becomes smaller. In the same time the volume of the spectator matter causing the shadowing is reduced, while the number of baryons involved in the fireball region increases, contributing to larger expansion [19,20,21]. All these effects play a role in the observed experimental azimuthal distributions.

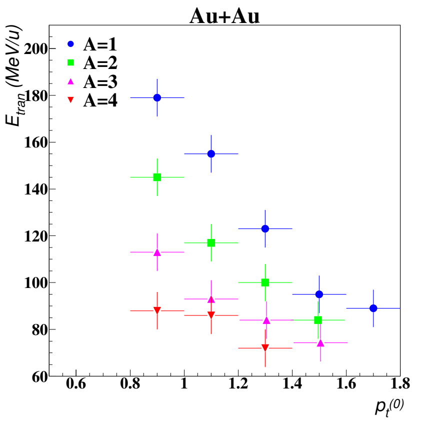

Figure 2. E_{tran} values as a function of $p_t^{(0)}$ for CM3 centrality and A=1,2,3 and 4.

However, the centrality dependence of the E_{tran} suggests that the reduction of the rotational motion of the fireball is the main source of the observed effect. Preliminary comparison with the IQMD (Isospin Quantum Molecular Dynamics) [22] indicates that both versions, HM (hard EoS - K=380 MeV, momentum dependent nucleon interaction) and SM (soft EoS - K=200 MeV, momentum dependent nucleon interaction) show the same qualitative behaviour of E_{tran} as a function of centrality; quantitatively the HM version predicting higher E_{tran} values than SM one. We have to mention here that the results presented above, peformed in the system of coordinate rotated with the sidwards flow angle relative to the beam direction, are based on corrected squeeze-out signals using a new method, recently proposed by Ollitrault [23],

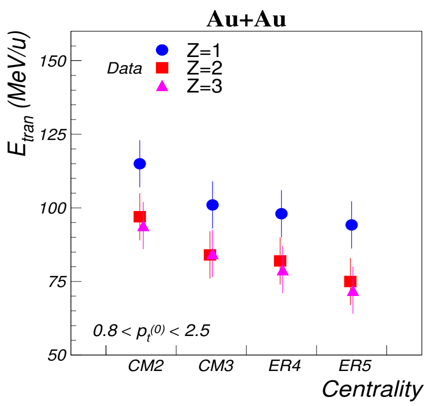

Figure 3. E_{tran} - centrality dependence for Z=1,2 and 3 reaction products.

deviced for the laboratory system. A consistent correction procedure is in progress. While the correction plays an important role on the absolute values of the squeeze-out signal, the preliminary results show that the effect on E_{tran} values is within the error bars.

2 Incident energy dependence of the mean kinetic energy, flow and temperature azimuthal distributions

The squeeze-out phenomena initially predicted by hydrodynamical calculations [8] has been extensively studied experimentally [9,10,11,24]. A unified representation of the observed trends can be done in terms of the azimuthal distribution of the total mass [25] or kinetic energy [4]. Previously reported comprehensive description of the squeeze-out phenomena in the range 0.25 - 1.15 A·GeV [25] was based on the parametrization of the total mass spectra with an expresion characteristic for radially symmetric shell expansion. As far as such a situation can hardly be encountered in heavy ion collisions and is not specific at all for mid-central geometries, we prefer to present also the experimental information free of any model which can be used to extract it.

Due to this reasons we report also the results on azimuthal distribution of the mean kinetic energy ($< E_{kin}^{cm} >$) besides the ones corresponding to β and T values. The azimuthal distributions of $< E_{kin}^{cm} >$, β and T can be fit with the following expresion: $(< E_{kin}^{cm} >, \beta, T) = (< E_{kin}^{cm} >, \beta, T)_0$ - $(\Delta < E_{kin}^{cm} >, \Delta\beta, \Delta T)\cdot\cos 2\Phi$. The excitation functions of $(< E_{kin}^{cm} >, \beta, T)_{max}$ and $(< E_{kin}^{cm} >, \beta, T)_{min}$ from 90 A·MeV to 400 A·MeV are represented in Fig.4. The elipsoidal character of the flow with the major axis perpendicular to the reaction plane constantly enhances from 90 to 400 A·MeV.

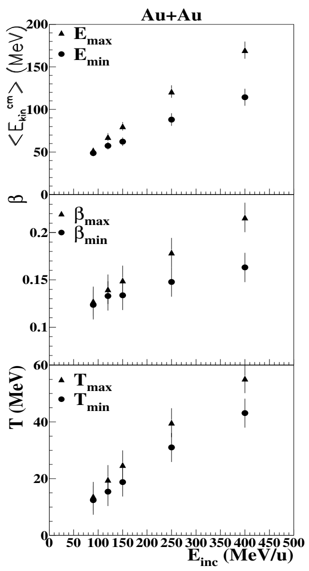

Figure 4. Excitation function for out-off-plane and in-plane $< E_{kin}^{cm} >$, β and T values for ER4 centrality and Z=2 fragments.

The lower slope in $(E,\beta,T)_{min}$ is due to the fact that the violence of the expansion increases faster as a function of incident energy than the decrease of the passage time. At higher incident energy the relativistic contraction and the gradient of the thermal pressure in the reaction plane due to the confinement created by the spectator matter are increasing. The two slopes reverse and a crossing point is expected. It would correspond to an elliptic flow with the major axis aligned in the reaction plane [26,27].

A larger modulation in the mean kinetic energy or flow relative to temperature can be explained by the larger variation of the expansion relative to the temperature as a function of break-up time [18,28].

3 Polar angle- and A_{part}- dependence of the correlated motion in heavy ion central collisions

Highly central collisions (1% cross section) have been slected using $E_{rat} = \sum_i E_{\perp,i}/\sum_i E_{||,i}$ observable, where i reffers to all particles identified by our detector. The experimental average kinetic energies represented as a function of mass of the corresponding reaction products show a linear dependence. The extracted slopes from such representations are presented in Fig.5 as a function of incident energy for the three symmetric systems and for two polar regions, $\theta_{cm} \in$ (25°-45°) (with a condition in azimuth of $\phi \in$ (90°(270°) $\pm$ 45°)) and $\theta_{cm} \in$ (80°-100°). One could easily follow the difference between the extracted slopes, representing the amount of the correlated motion per nucleon, in the forward and transversal direction relative to the collision axis. While in the forward region ($\theta_{cm} \in$ (25°-45°)) no dependence of the extracted slopes on the mass of the colliding systems is observed, in the transversal direction ($\theta_{cm} \in$ (80°-100°)) the dependence on the the barionic content of the fireball is quite clear.

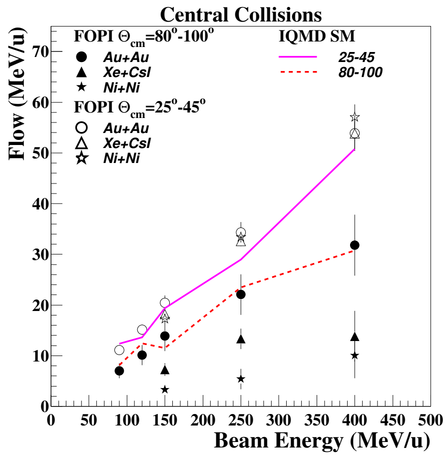

Figure 5. Excitation function for the correlated motion for Au+Au, Xe+CsI and Ni+Ni in two polar regions and comparison with the IQMD-SM model predictions.

The continuous and dashed lines represent the results of IQMD - SM estimates of the corresponding slopes for Au + Au in the corresponding polar regions. The agreement with the experimental data is quite satisfactory. IQMD simulations show a dependence of the average number of collisions per nucleon as a function of polar angle. In the average 2 times more colisions are suffered by the nucleons emitted in the transversal direction relative to the forward ones. The experimental trends corroborated with the results of the microscopic approach bring to the conclusion that the higher values of the slopes and their independency on the barionic content of the fireball in the forward direction is mainly due to transparency effect. A better estimate of the amount of expansion and its dependence as a function of the participating number of nucleons is visible in the transverse direction relative to the collision axis where the contamination from other effects has the lowest value.

4 Conclusions

Using a new generation of data collected with the complete FOPI experimental device we performed a systematic study of the azimuthal- and polar angle-dependence of the flow phenomena in semi-central and respectively central heavy ion collisions based on reaction products composed of few nucleons. A clear transition from in-plane (rotational-like) to out-of-plane (squeeze-out) was evidenced. The incident energy at which this transition takes place - E_{tran}, was studied as a function of mass of reaction products, their scaled transverse momentum ($p_t^{(0)}$) and centrality. The excitation functions of in- and out-off-plane $< E_{kin} >^{cm}$, β and T show that the elipsoidal character of the flow with the major axis perpendicular to the reaction plane constantly enhances from 90 to 400 A·MeV. A clear polar angle- and A_{part}-dependence of the correlated motion in highly central collisions was evidenced. Microscopic transport model (IQMD) calculations predict the same qualitative behaviour of E_{tran} as a function of centrality. Soft EoS explains better the trends observed in highly central collisions.

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