SPECIAL ASPECTS OF THE BARYONIC FLOW IN RELATIVISTIC HEAVY ION COLLISIONS

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FOPI COLLABORATION

Specific experimental results and qualitative and quantitative comparisons with model predictions relative to the azimuthal and polar angle dependence of the flow phenomena in semi-central and respectively central heavy ion collisions are presented.

1 Introduction

After about three decades of theoretical and experimental studies of relativistic heavy ion collisions the question of equation of state (EoS) of nuclear matter produced in such collisions does not have yet a definite answer. Dynamical effects, local thermal and chemical equilibration, momentum dependent interaction and in medium effects turned out to play an important role. Complete and accurate experimental information turned out to be mandatory for understanding these effects using realistic force in transport microscopic calculations. Based on this force one could calculate the equation of state of nuclear matter. The results presented here are based on a series of experiments on symmetric heavy ion collisions at energies between 90 and 400 A·MeV using a complete configuration of the FOPI setup. Details on the experimental configuration and analysis technique can be found elsewhere [1,2,3,4,6,7].

Section 2 is dedicated to the experimental results on transverse momentum and reaction product dependence of the incident energy where a transition from in-plane to out-of-plane azimuthal enhancement takes place. Qualitative explanations of the observed trends based on a semi-analytical hydrodynamical model are presented. The influence of the baryonic and N/Z content of the spectator matter on the mean kinetic energy and yield azimuthal distributions, respectively are analysed in Section 3. In Section 4 is presented the polar angle- and A_{part}-dependence of the azimuthally symmetric correlated motion in highly central collisions. Conclusions are presented in Section 5.

2 Transition energy - transverse momentum and reaction product dependence

Detailed studies of the incident energy at which the azimuthal distributions change their character from an in-plane, rotational-like to an out-of-plane, squeeze-out pattern have been done in the last period [9,10,11,4,12,13,6,5,18]. For a given centrality range, transverse momentum and mass of the analysed 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 incident energy corresponding to $R_N = 1$ value is defined as transition energy - E_{tran}. Fig.1 shows the experimental E_{tran} values as a function of scaled transverse momentum $p_t^{(0)} = (p_t/A)/(p_P^{cm}/A_P)$ for different reaction products for a centrality corresponding to 4-6 fm impact parameter interval. A continuous decrease of the E_{tran} value as a function of $p_t^{(0)}$ is evidenced for all analysed particles and the difference in E_{tran} values for different particles for a given $p_t^{(0)}$ is decreasing towards larger values of $p_t^{(0)}$. For a rotating emitting source one would expect a larger in-plane alignment for heavier fragments [10]. 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. For this centrality the number of participating nucleons is about 200.

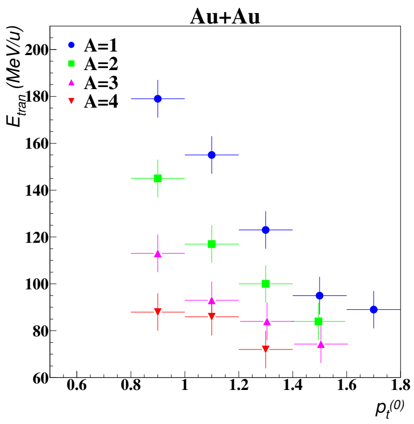

Figure 1. E_{tran} values as a function of $p_t^{(0)}$ for CM3 centrality and A=1,2,3 and 4.

For such a fireball we calculated the expansion dynamics using a semi-analitical hybrid model [14]. A two dimensional $p_t^{(0)}$ versus break-up time of the yield distribution for p, d, α and Li fragments can be followed in Fig.2 At large $p_t^{(0)}$ the contribution comes from the same range in the break-up time for all particles, corresponding to large expansion velocities. As far as the squeeze-out signal is the largest at high $p_t^{(0)}$, it follows that at this break-up times the shadowing reaches the maximum value. 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. One could observe also that heavier fragments at lower $p_t^{(0)}$ are preferentially produced later in the expansion process relative to the light ones.

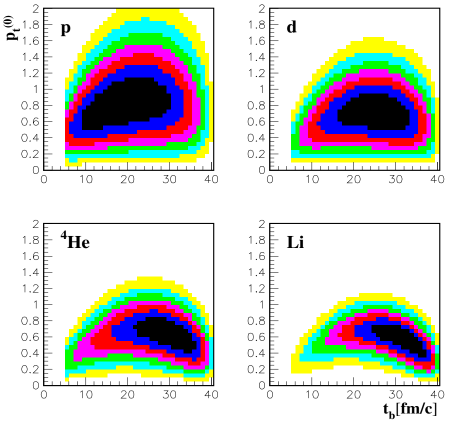

Figure 2. $p_t^{(0)}$ - break-up time distribution for A=1,2,4 and 7 reaction products

During the expansion process the rotational-like motion of the source is attenuated by the faster emitted particles, the slower ones being exposed at weaker rotational effect - in-plane alignement. Detailed comparison with predictions of microscopic transport codes is on the way, the main difficulty coming from the low statistics of IMFs produced by them.

3 The influence of the baryonic and N/Z spectator matter content on the azimuthal distributions

Incident energy excitation functions of the azimuthal distributions of flow, temperature or mean kinetic energy for different particles, different centralities and mass of the colliding systems are of real interest for deeper understanding of the expansion mechanism. They could be used to discriminate between pressure gradient or simple preequilibrium or shadowing contributions to the observed azimuthal anisotropies [16,17,18]. In this contribution we will concentrate on the influence of the baryonic and N/Z content of the spectator matter on the azimuthal distributions which seems to be sensitive observables to the in medium nucleon-nucleon interaction and its isospin dependence.

$< E_{kin}^{cm} >$ azimuthal distributions for different reaction products follow a $< E_{kin}^{cm} > = E_0$ - ΔE·cos2Φ behaviour. E_{max}=E_0 + ΔE and E_{min}=E_0 - ΔE corresponding to out-of-plane and respectively in-plane mean kinetic energies and 2·ΔE values for Au + Au, Xe + CsI, Ni + Ni, CM3 centrality (4-6 fm), at 250 A·MeV, Z=2 fragments, as a function of A_{part} (the number of

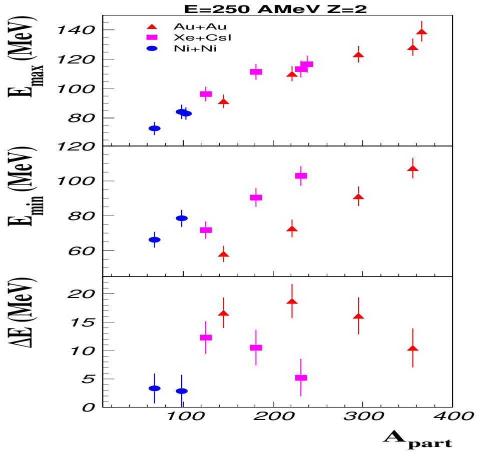

Figure 3. E_{max}, E_{min} and 2·ΔE as a function of A_{part}

the participaing nucleons estimated using straight trajectories) can be followed ig Fig.3. The out-of-plane mean kinetic energy E_{max} shows almost a linear dependence as a function of A_{part} with minor difference between different systems (aspect ratio of the overlaping zone) while a large differences in E_{min} between the three systems is observed. Simple geometrical considerations (see Fig.4,5) show that for A_{part}=200 nucleons, while the aspect ratio of Au+Au and Xe+CsI differ by 20%, the thickness of the spectator matter in the reaction plane varies by almost a factor of three. As far as small changes in the aspect ratio do not show large effects in the mean kinetic energy in the region not hindered by the spectators and the difference in the transit time is of the order of 1 fm/c, the conclusion is that the thickness of the spectator matter is the main reason

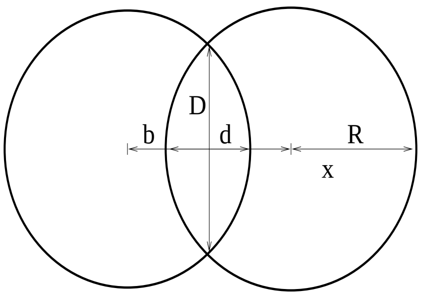

Figure 4. Collision geometry projected on a plane perpendicular to the collisions axis

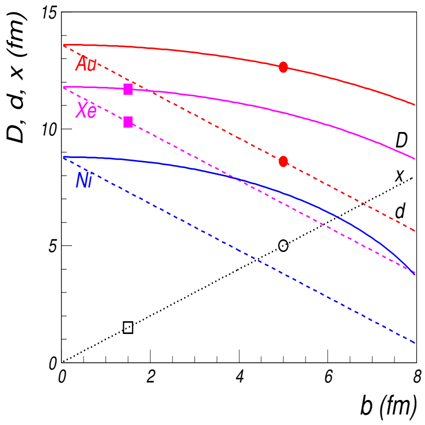

Figure 5. The fireball semiaxis and the in-plane spectator thickness for the projection presented in Fig.4

for the observed difference in the E_{min} values. What about the influence of the N/Z content of the spectator matter on the squeeze-out signal? Very preliminary results of such a study using the experimental data obtained by us in Ru + Zr and Zr + Ru collisions at 400 A·MeV are presented. The situation is schetched in Fig.6. Supposing that the fireball is equilibrated in

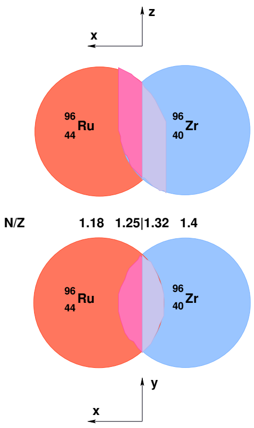

Figure 6. Collision geometry projected on the reaction plane - up and perpendicular to the collisions axis - down. N/Z values corresponding to different zones for 5 fm impact parameter are indicated.

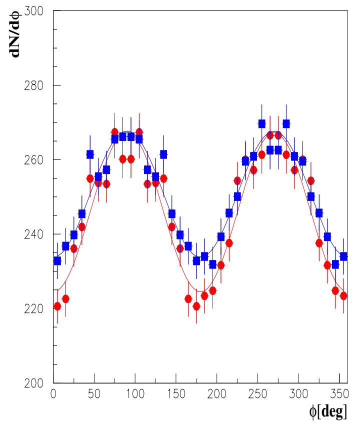

Figure 7. Azimuthal proton distributions for Ru + Zr (dots) and Zr + Ru (squares) measured between 0-90 and 270-360 deg and reflected relative to 90 and 270, respectively

N/Z we have to do with an expanding object in the presence of spectator matter asymmetric in N/Z. As far as the asymmetry is very small, the effect is expected to be also small. For this reason we performed our studies in a system of coordinates rotated by the sidewards flow angle. Breaking in this way the azimuthal symmetry of the experimental device we had to symmetrise the experimental distributions obtained in the azimuthal range 0-90 deg and 270-360 deg relative to 90 deg and 270 deg respectively in order to obtain the complete azimuthal distribution. The results for 4-6 fm centrality and a range in the scaled transverse momentum of 0.8-1.2 can be followed in Fig. 7 for protons. Although quite preliminary, the result seems to indicate an influence of the N/Z value of the spectator matter on the observed distributions. This could become a sensitive probe for studying the isospin dependence of the in-medium nucleon-nucleon interaction used in microscopic transport codes.

4 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 $E_{rat} = \sum_i E_{\perp,i} / \sum_i E_{\parallel,i}$ 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.8 as a function of incident energy for the three symmetric systems and for two polar regions, $\theta_{cm} \in (25°\text{-}45°)$ (with a condition in azimuth of $\phi \in (90°(270°) \pm 45°)$) and $\theta_{cm} \in (80°\text{-}100°)$.

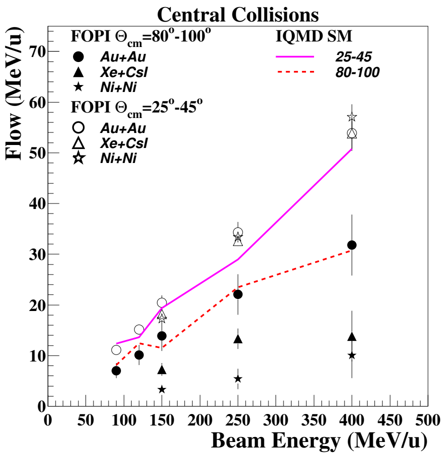

Figure 8. Excitation function for the correlated motion for Au+Au, Xe+CsI and Ni+Ni in two polar regions and comparison with the IQMD-SM model predictions

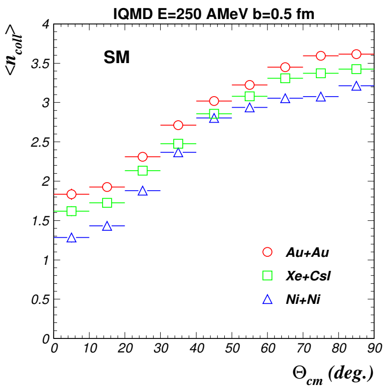

Figure 9. The average number of collisions of each nucleon as function of c.m. polar angle, predicted by IQMD model.

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 ($\theta_{cm} \in (25°\text{-}45°)$) no dependence of the extracted slopes on the mass of the colliding systems is observed, in the transversal direction ($\theta_{cm} \in (80°\text{-}100°)$) the dependence on the baryonic content of the fireball is quite clear.

The continuous and dashed lines represent the results of IQMD - SM[15] 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, see Fig. 9. In the average two 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 baryonic 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.

5 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. Clear transverse momentum and reaction product dependence of the E_{tran} value has been evidenced in the experimental data. Qulitative explanations of these trends could be understood in the frame of a semianalitical hybrid model which predicts a breakup which, with elapsing time, starts at the outer shells and evolves to inner ones. Using three symmetric systems and selecting the geometry such to have the same baryonic content of the fireball, it was clearly evidenced the role of the spectator matter for the observed kinetic energy azimuthal distributions. Preliminary results on the azimuthal distributions for Ru+Zr and Zr+Ru indicate an influence of the N/Z value of the spectator matter on the squeeze out phenomena. A clear polar angle- and A_{part}-dependence of the correlated motion in highly central collisions was evidenced. Soft EoS in a microscopic transport model (IQMD) explains better the trends observed in highly central collisions.

Acknowledgments

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