Analysis of squeeze-out for fragments *

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Abstract:

The azimuthal distribution of fragments at midrapidity shows an enhancement of the *squeeze-out* effect for light fragments as compared to protons. This enhancement increases with increasing transverse momenta of the fragments. Fragments close to projectile or target rapidity are strongly correlated with the reaction plane. This is the result of microscopic QMD calculations in which realistic momentum dependence forces have been employed. The squeeze-out, i.e. the preferred emission of particles perpendicular to the reaction plane, is more pronounced for fragments as compared to protons.

One of the basic motivations to study relativistic heavy ion collisions is the possibility to produce nuclear matter at high density and temperature. Early hydrodynamical calculations predicted two collective effects which occur during the collision of two finite nuclei: the transverse flow *in the reaction plane* (bounce-off) and the emission of high energetic particles *perpendicular to the reaction plane* (squeeze out)[1]. Both effects have been confirmed by experiments and quantitative calculations have been performed in various microscopic models.

Whereas the bounce is dominated by cold matter which is reflected by the high density overlap region of projectile and target, the squeeze is caused by hot matter which has been stopped and therefore is centered around midrapidity.

In this article we will investigate the dynamics of fragments at midrapidity. This is of special interest because for single nucleons the collectivity of the squeeze is washed out by nucleon nucleon collisions. Fragments, in which the nucleons have to have about the same momenta and therefore are not that much affected by collisions should show this collective effect much clearer.

For our calculations we used the Quantum Molecular Dynamics model [2] in an extended version including the isospin degrees of freedom for nucleons, deltas and pions[3]. In this model the particles are propagated according to Hamilton's equations of motion. The real part of the G-Matrix is approximated by a local density dependent two- and three-body, a Yukawa- and an asymmetry potential, which is derived from the Bethe Weizsaecker mass formula. These potentials are supplemented by the Coulomb potential. The parameters are adjusted to reproduce the optical potential up to 1 GeV and a compressibility of 200 MeV. The imaginary part of the G-Matrix is described by binary hard core collisions using experimental cross sections and energy dependent angular distributions in the elastic and

inelastic channels. Isospin is explicitely included into all collision channels. The Pauli principle is obeyed by allowing only those collisions where the final state is not occupied by other nucleons. The fragments are obtained by regarding correlations in coordinate space using a spanning tree method[4].

Figure 1 shows the normalized azimuthal distributions $\frac{d^2N}{d\varphi\,\Delta Y}$ of the particles in the laboratory frame at center-of-mass rapidity obtained from a IQMD calculation for Au+Au at 400 MeV incident energy at an impact parameter of $b = 3$ fm. φ denotes the angle between the transverse momentum vector $\vec{p}_T$ and the reaction plane defined by the z (beam) - and the x (impact parameter) axis. $\varphi = 0$ resp. $\varphi = 180$ degrees correspond to the positive resp. negative x axis, $\varphi = \pm 90$ degrees characterize the direction perpendicular to the scattering plane.

We see minima at 0 and 180 degrees (i.e. in the *in plane* p_X-direction) and maxima *out of plane*, namely at 90 and -90 (resp. 270) degrees (i.e. in the p_Y-direction *perpendicular to the scatter plane*). This means that *at midrapidity* more particles are pressed out perpendicular to the reaction plane than in the reaction plane.

From the left part of Fig. 1 we see that the peak at $\varphi = 90^0$ degrees becomes much more prominent if we rotate the system by the flow angle Θ_{flow} in the reaction plane instead using the lab-system (with the beam defining the z-axis). The flow angle is obtained by diagonalizing the sphericity tensor[5] using as weight the absolute value of the momentum:

$$P_{ij} = \sum_{k=1,A} \omega_k \, p_i(k) p_j(k) \qquad i,j = 1,2,3 \quad (x,y,z) \qquad \omega_k = \frac{1}{|\vec{p}(k)|}$$

If we are in the eigensystem of the momentum ellipsoid, we define the p'_z-axis to be the largest axis of the ellipsoid and the p'_x-axis to be the axis, which is still in the reaction plane described by the p_x and p_z-axes of the lab-system. Thus, the p_y and p'_y axes point into the same direction. The transverse momentum in the rotated system is defined as the

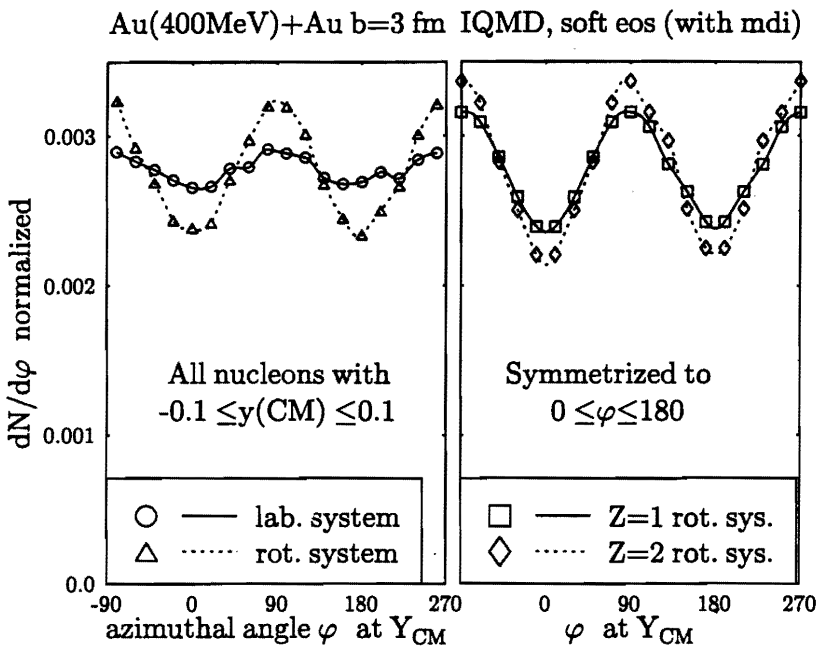

Figure 1: Azimuthal distribution of nucleons at midrapidity. The left hand side shows the difference between the labsystem and the rotated eigensystem of the sphericity tensor. The right hand side shows (in the rotated system) the difference between charge $Z = 1$ and $Z = 2$ particles. The data on the rhs. have been taken in the $0 \leq \varphi \leq 180$ degree range and been symmetrized to the whole angular range.

component perpendicular to the p_z axis. The azimuthal angle φ is now the inclination angle between the transverse momentum in the rotated system and the p'_x-axis. The azimuthal distributions in the *principal axis system* ('rotated system') yield a clearly stronger signal.

The right part of Fig. 1 describes the azimuthal distribution in the rotated (i.e. principal axis) system for particles with charges $Z = 1$ and $Z = 2$, respectively. A visible difference can be found. The $Z = 2$ particles show a stronger emission *out of plane* than $Z = 1$ indicating that light fragments at midrapidity exhibit a stronger correlation perpendicular to the reaction plane than single nucleons. The strength of this enhancement depends on the nuclear equation of state and the in-medium cross sections [6]. Momentum dependent interactions seem not to change the azimuthal distribution significantly. However, influences of the momentum dependent interactions on the azimuthal distributions of particles with very high transverse momenta have recently been reported.[7]

Let us characterize the azimuthal distributions by the ratio of the yields *out-of-plane* to *in-plane*.

$$R_N = \left. \frac{\frac{dN}{d\varphi}(\varphi = 90^0) + \frac{dN}{d\varphi}(\varphi = 270^0)}{\frac{dN}{d\varphi}(\varphi = 0^0) + \frac{dN}{d\varphi}(\varphi = 180^0)} \right|_{Y=Y(CM)}$$

Of course this value can again be taken in the rotated as well as in the unrotated system.

Since the azimuthal distribution can be fitted with two cosine functions

$$\frac{dN}{d\varphi} = a_0 \cdot \{a_1 \cos(\varphi) + a_2 \cos(2\varphi)\}$$

where a_1 vanishes at midrapidity the ratio R_N can be written as

$$R_N = \frac{1 + a_2}{1 - a_2}$$

For our calculation we therefore took azimuthal bins at $\varphi = \varphi_0 \pm \Delta\varphi$ with $\Delta\varphi = 20°$ and

calculated the ratios

$$R_N^{bin} = \left.\frac{\frac{dN}{d\varphi}(\varphi = 90^0 \pm \Delta\varphi) + \frac{dN}{d\varphi}(\varphi = 270^0 \pm \Delta\varphi)}{\frac{dN}{d\varphi}(\varphi = 0^0 \pm \Delta\varphi) + \frac{dN}{d\varphi}(\varphi = 180^0 \pm \Delta\varphi)}\right|_{Y=Y(CM)}$$

and corrected with the integral of the $\cos(2\varphi)$ function in the azimuthal bin

$$R_N = \frac{R_N^{bin}(1+\delta) + (1-\delta)}{R_N^{bin}(1-\delta) + (1+\delta)} \qquad \delta = \frac{2\Delta\varphi}{\sin(2\Delta\varphi)}$$

In Figure 2 we see this ratio taken in the rotated system as a function of the fragment mass A_f. There is a slight increase in R_N with A_f if we do not use additional cuts in the transverse momentum, as it could be seen in Fig. 1. If we now select for high momentum particles with

$$p_T/A_f > aP_{Proj}(CM), \qquad P_{Proj}(CM) = 433\,MeV/c, \qquad a = 0.5,\ 0.7,\ 1$$

where $P_{Proj}(CM) = 433\text{MeV/c}$ (for the incident energy $E_{lab} = 400$ MeV) denotes the incident projectile momentum per nucleon taken in the CM-frame, the ratios increase strongly. The increase with the transverse momentum corresponds to the higher mean transverse momentum of the particles at 90 degrees out-of plane as it has been reported by experiment [8] and calculations [6]. Recent experimental[9] and theoretical [7] investigations on the dependence of R_N (in the lab frame) on p_T/P_{Proj} only found a weak dependence of $R_N(p_T/P_{Proj}$ on the incident energy for $E_{inc} = 400 \ldots 1000\text{MeV}$.

The cut on the transverse momentum has a drastic effect on the squeeze-out of light fragments. We see a dramatic increase of R_N with the fragment mass, if a high transverse momentum cut is used. For light fragments R_N reaches factors of 3 and 4 and possibly higher. This strong dependence of the squeeze on the fragment mass underlines the importance of collectivity for the squeeze-out.

Do fragments show a strong preference perpendicular to the reaction plane? For light fragments stopped at midrapidity this questions can be clearly answered with yes. However

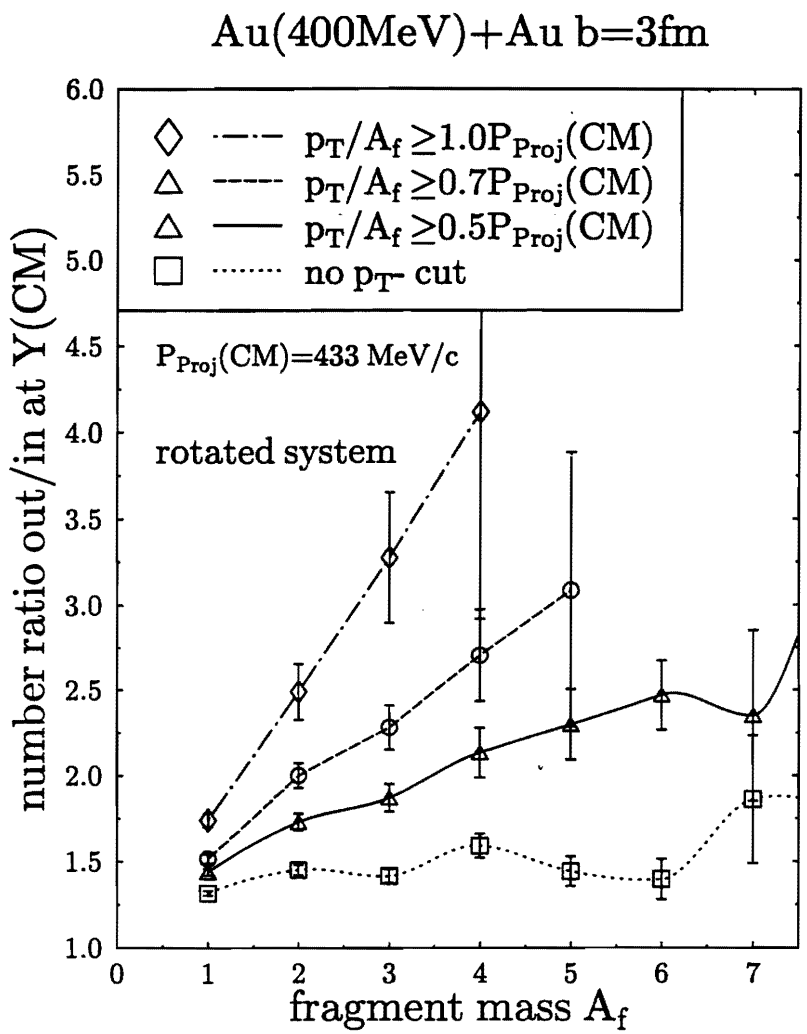

Figure 2: The out-of-plane to in-plane ratio R_N in the rotated system as a function of the fragment mass A_f. An analysis without transverse momentum cuts is compared to fragments with p_T/A_f larger than 0.5 P_{Proj}, 0.7 P_{Proj} and 1 P_{Proj}. P_{Proj} = 433MeV/c is the incident projectile momentum per nucleon taken in the CM frame.

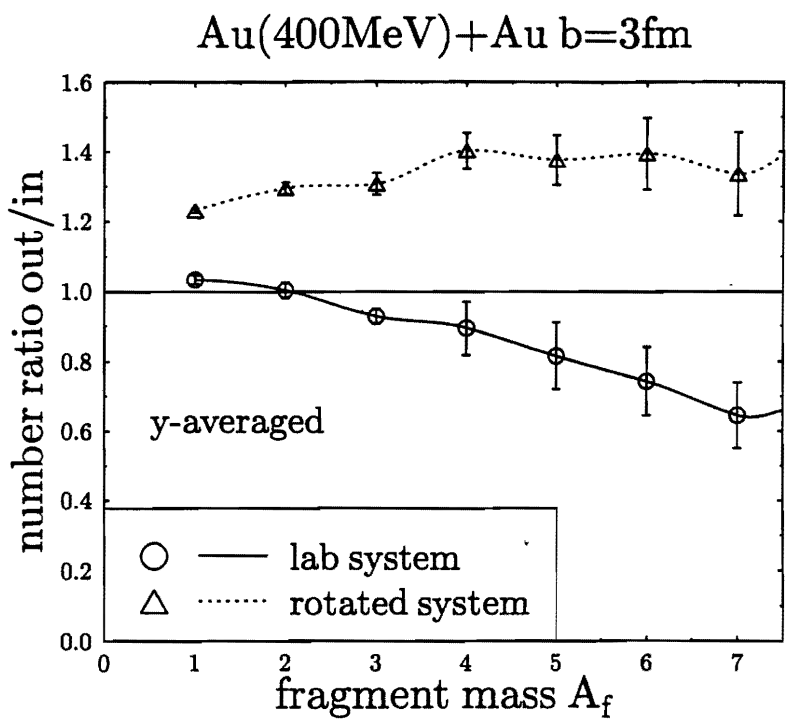

Figure 3: Comparison of the out-of-plane to in-plane ratio of fragments from all rapidities taken in the lab system and in the rotated system.

the situation changes if we integrate the distibution over the whole rapidity range. Fig. 3 presents the out-of-plane to in-plane ratio of the fragments averaged over all rapidities. If we take the out-of-plane to in-plane ratio in the rotated system the values remain larger than 1. This denotes that the projection of the momentum distribution onto the p'_x-p'_y plane yields a stronger width of the distribution in p'_y direction than in the p'_x direction.

In the lab system we see a decrease with the fragment mass. For light fragments values smaller than 1 are reached indicating a stronger correlation in the reaction plane. In the lab-frame we project a distribution with the shape of an rotated ellipsoid onto the p_x-p_y plane. Therefore the contribution of particles at projectile-rapidity will cause large positive p_x values and the particles at target-rapidity will strongly contribute at large negative p_x values. This corresponds to the large in-plane flow of the fragments where $< p_x(y) >$ reaches high values at projectile rapidity[4]. Since the fraction of stopped particles decreases with increasing fragment mass, more and more fragments are found at projectile and target rapidities. Therefore the momentum distribution of larger fragments is dominated by these particles near projectile and target rapidities which strongly participate to the flow in plane, see also Fig.4.

The latter effect was predicted in ref.[10, 11, 2, 4] and observed experimentally [12]. Recent measurements at the Bevalac and SIS facilities confirmed these observations with higher accuracies[13]. Fig. 4 shows the dependence of the mean transverse momentum transfer per nucleon p_x^{dir}/A_f on the fragment mass. In the lab system we see an increase of the in-plane flow with the fragment mass. If we now turn to the rotated system the values decrease. Here we see a remnant of the **bounce-off** of spectator matter. The intermediate mass fragments are scattered from the high density region but do not loose very much of their longitudinal momentum. Since the momentum distribution of the fragments

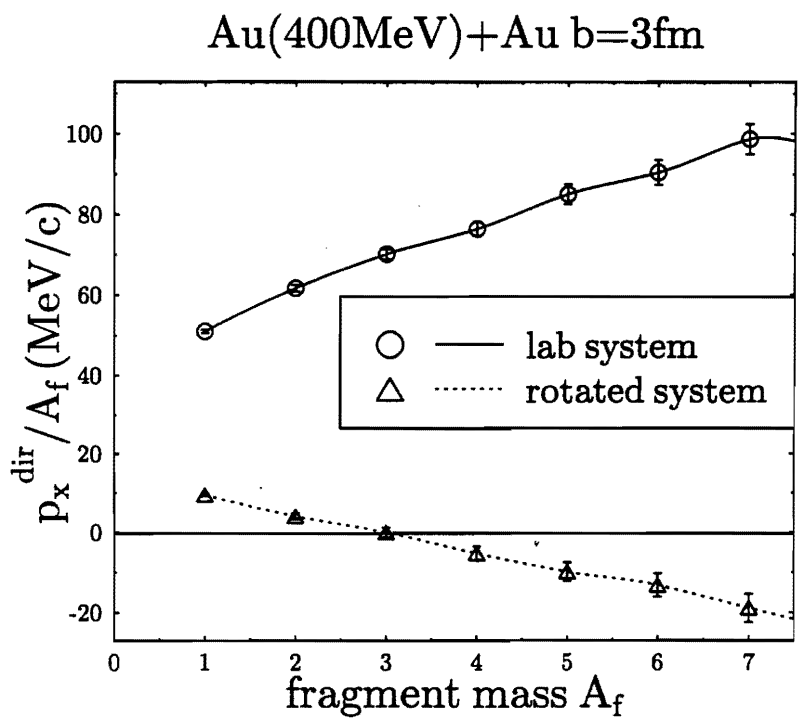

Figure 4: Mean momentum transfer per nucleon p_x^{dir}/A_f as a function of the fragment mass taken in the lab system and in the rotated system.

is strongly dominated by the particles at projectile and target rapidities, the flowangle of fragments is somehow smaller than that of the single particles whose momentum distribution is stronger dominated by stopped particles. This also corresponds to the fact that the extrapolation of the slope of the flow (which is taken at CM rapidity) to projectile rapidity yields higher values than $< p_x >$ taken at $y_{Projectile}$ (this just characterizes the S-shape of the curve!). Therefore the fragments seem to show a negative flow in the rotated system since the shape of the momentum ellipsoid is dominated by the light particles.

In conclusion, we have demonstrated that microscopic QMD calculations predict the observed collective *off-plane-squeeze-out* of nuclear matter. Fragments stopped to midrapidity show an enhanced *squeeze-out* effect, which can be most strongly seen for high transverse momentum light fragments. Nevertheless over all rapidities light fragments show a stronger correlation towards the reaction plane.

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