Disappearance of flow

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We investigate the disappearance of collective flow in the reaction plane in heavy-ion collisions within a microscopic model (QMD). A systematic study of the impact parameter dependence is performed for the system Ca+Ca. The balance energy strongly increases with impact parameter. Momentum dependent interactions reduce the balance energies for intermediate impact parameters $b \approx 4.5$ fm. For the heavy system Au+Au, dynamical negative flow is not visible in the laboratory frame but does exist if the initial precontact rotation of the system due to the Coulomb potential is subtracted. For semiperipheral collisions of Ca+Ca with $b \approx 6.5$ fm a new two-component flow is discussed. Azimuthal distributions exhibit strong collective flow signals, even at the balance energy.

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I. INTRODUCTION

The prediction of collective flow in heavy-ion collisions by the hydrodynamical model [1] has yielded a powerful tool for the investigation of excited nuclear matter. The main goals are to determine the equation of state (EOS) and the in-medium nucleon-nucleon cross section. One possible approach is the measurement and calculation of the transverse flow in the reaction plane. At beam energies above 100–200A MeV two-body collisions rule the dynamics yielding the typical bounce-off behavior [2–5], which is the deflection of cold spectator matter from hot compressed participant matter. The attractive part of the mean field becomes more and more important with a decrease in energy. As a consequence even negative scattering angles are possible [6] which can be imagined as partial orbiting of the two nuclei [7]. At a certain incident energy, called the balance energy $E_{\rm bal}$, the attractive and repulsive forces which are responsible for the transverse flow in the reaction plane cancel each other, causing the disappearance of this particular flow characteristic.

The notation "energy of vanishing flow," as the balance energy is often called, can lead to misunderstandings: In particular, we will demonstrate by inspecting azimuthal distributions that strong flow still exists at the balance energy. Whereas it was shown for small impact parameters that the balance energy depends only weakly on the stiffness of the equation of state [8,9], a large sensitivity to the nucleon-nucleon in-medium cross section was recognized [8,9,7]. The functional dependence of the balance energy on the system size can be approximately described by a power law $E_{\rm bal} \sim A_{\rm tot}^{-\frac{1}{3}}$ [10,7]. Systematic studies of the mass dependence of the disappearance of flow proposed a reduction of the in-medium cross section of about 20% with respect to the free NN cross section at normal nuclear density [7] by comparing the measured data [11–16,7] with Boltzmann-Uehling-Uhlenbeck (BUU) calculations. However, all investigations neglected to study the impact parameter dependence of the disappearance of flow.

In this paper we show that a variation of the impact parameter changes decisively the balance energy $E_{\rm bal}(b)$ and as a consequence the mass dependence analysis receives an important new variable. Also, the system Au+Au exhibits no negative flow in the laboratory frame. However, if the initial precontact rotation of the system due to Rutherford trajectories is subtracted, large negative flow appears. Furthermore, we newly observe a two-component flow in collisions with large impact parameters. We have also found that azimuthal asymmetries persist at the balance energy. Finally, the balance energy $E_{\rm bal}$ is nearly independent of particle type [7], although it is well known that the strength of the flow depends on it. Therefore we will mostly regard all nucleons and check the effect of taking clustering into account.

II. MODEL

The quantum molecular dynamics (QMD) model [9,17–22] is employed here. In the QMD model the nucleons are represented by Gaussian-shaped density distributions. They are initialized in a sphere of a radius $R = 1.12A^{1/3}$ fm, according to the liquid drop model. Each nucleon is supposed to occupy a volume of h^3, so that the phase space is uniformly filled. The initial momenta are randomly chosen between zero and the local Thomas-Fermi momentum. The A_P and A_T nucleons interact via two- and three-body Skyrme forces, a Yukawa potential, momentum-dependent interactions, a symmetry potential (to achieve a correct distribution of protons and neutrons in the nucleus), and explicit Coulomb forces between the Z_P and Z_T protons. Using this ansatz we have chosen a hard equation of state with a compressibility of $\kappa = 380$ MeV [23,24]. For the momentum-dependent interaction we use a phenomenological ansatz

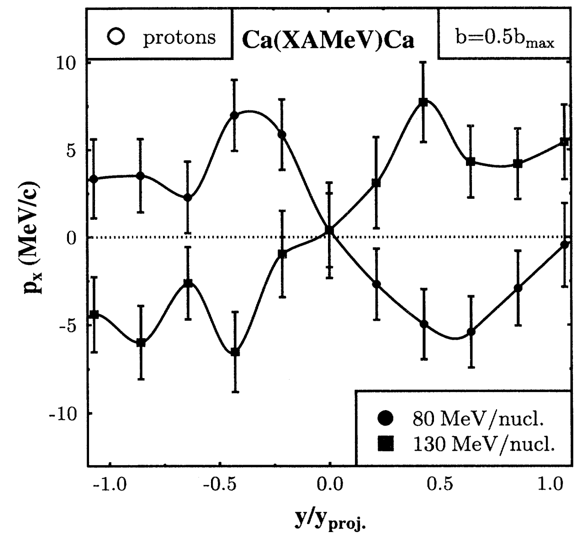

FIG. 1. Transverse momentum projected onto the reaction plane p_x as a function of the normalized rapidity. This $p_x(y/y_p)$ distribution of protons for the system Ca+Ca is plotted at the two incident energies, $80A$ MeV and $130A$ MeV. The impact parameter is half the maximum impact parameter $b = 0.5b_{\max}$. For each curve 1000 events were calculated with a hard equation of state without momentum-dependent interactions. The lines are plotted to guide the eye.

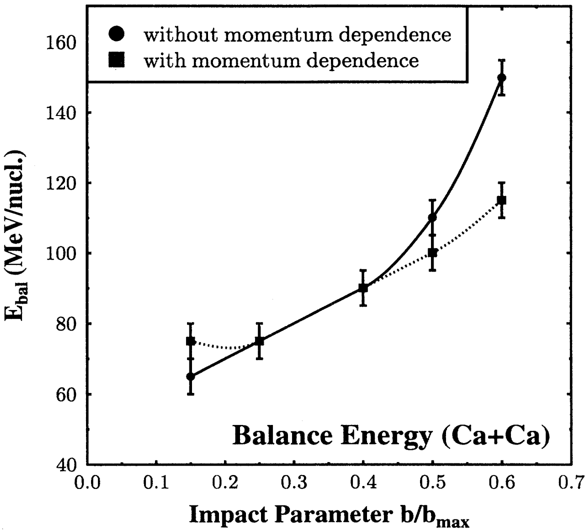

FIG. 3. The in-plane balance energy E_{bal} as a function of impact parameter b for the system Ca+Ca. The circles and squares are the calculated values without and with momentum-dependent interactions, respectively. The curves are plotted to guide the eye.

[25,18,26] which fits experimental measurements [27,28] of the real part of the nucleon optical potential. The nucleons are propagated according to Hamilton's equation of motion. A clear distinction is made between protons and neutrons with Coulomb forces acting only on the protons and an asymmetry potential containing the asymmetry term from the Bethe-Weizsäcker formula acting between protons and neutrons. Furthermore, parametrized energy-dependent free pn and pp cross sections are used instead of an averaged nucleon-nucleon cross section. They differ by 50% at 150 MeV. It was shown that their energy dependence cannot be neglected [29]. Hard NN collisions are included by employing the collision term of the well-known Vlasov-Uehling-Uhlenbeck- (VUU-) BUU equation [4,24,30–33]. The collisions are done stochasti-

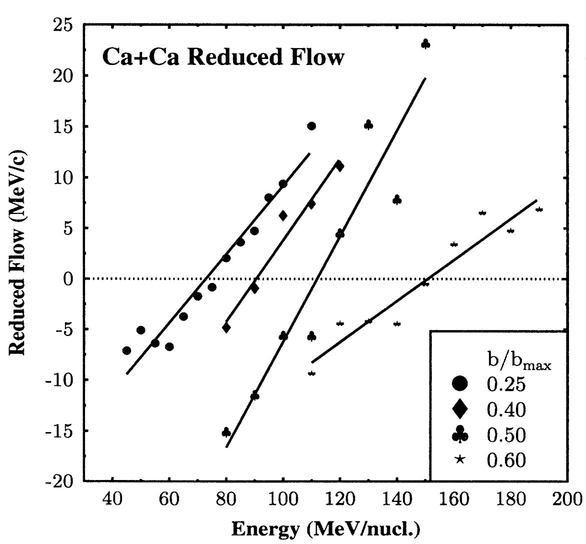

FIG. 2. Reduced flow values as a function of incident energy and impact parameter for Ca+Ca. The impact parameters are 0.25, 0.4, 0.5, 0.6 times the maximum impact parameter. Each point is a result of 1000 events with a hard equation of state without momentum dependence. The straight lines are the results of linear fits.

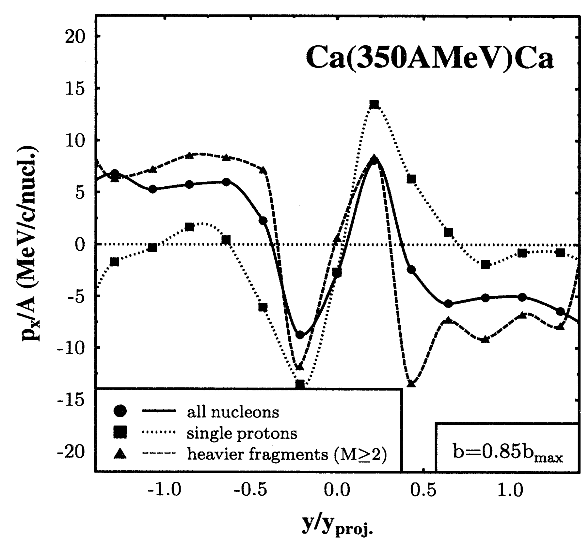

FIG. 4. $p_x/A(y/y_p)$ distributions of all nucleons, single protons, and heavier fragments for the semiperipheral ($b = 0.85b_{\max}$) collision of Ca+Ca at $350A$ MeV incident energy. This two-component flow is obtained from a calculation of 10 000 events with a hard equation of state without momentum-dependent interactions.

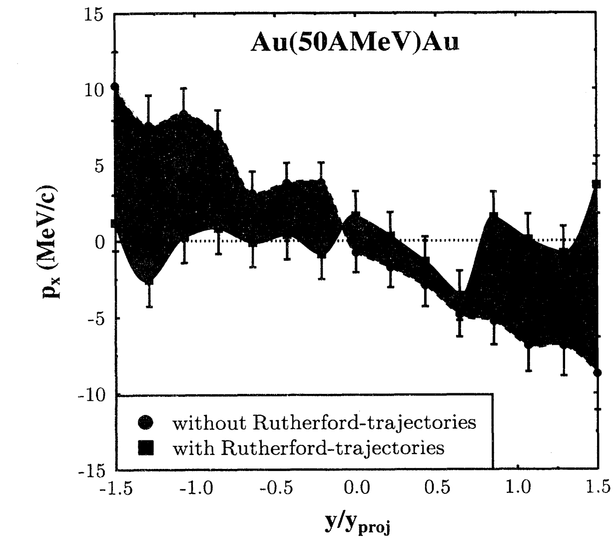

FIG. 5. $p_x(y/y_p)$ distribution of protons for the system Au+Au at 50A MeV. The impact parameter is $0.5b_{\max}$. The squares and circles correspond to calculations with and without an initialization on Rutherford trajectories. Five hundred events were calculated for each curve with a hard equation of state without momentum dependence.

cally, in a similar way as in the cascade models [34,35]. In addition, the Pauli blocking (for the final state) is taken into account by regarding the phase space densities in the final states of a two-body collision.

III. RESULTS AND DISCUSSION

For the investigation of transverse flow in the reaction plane the in-plane transverse momentum p_x is usually plotted versus the normalized rapidity y/y_p. Figure 1 shows the $p_x(y)$ distribution at two different energies for the system Ca+Ca and $b = 0.5b_{\max} \approx 4$ fm. At 80A MeV a negative slope (corresponding to negative scattering angles) is visible whereas for 130A MeV the opposite sign (positive scattering angles) is found. The first corresponds to negative scattering angles of the majority of the protons; the latter illustrates the deflection of nucleons caused by nucleon-nucleon collisions.

In order to determine the balance energy, the energy is varied between these two values and a linear fit is applied to the slopes of the $p_x(y)$ distributions. These slopes, which are called reduced flow, have negative values for energies smaller than E_{bal} and positive values for energies higher than E_{bal}. The balance energy E_{bal} is obtained again by a linear fit to the energy depen-

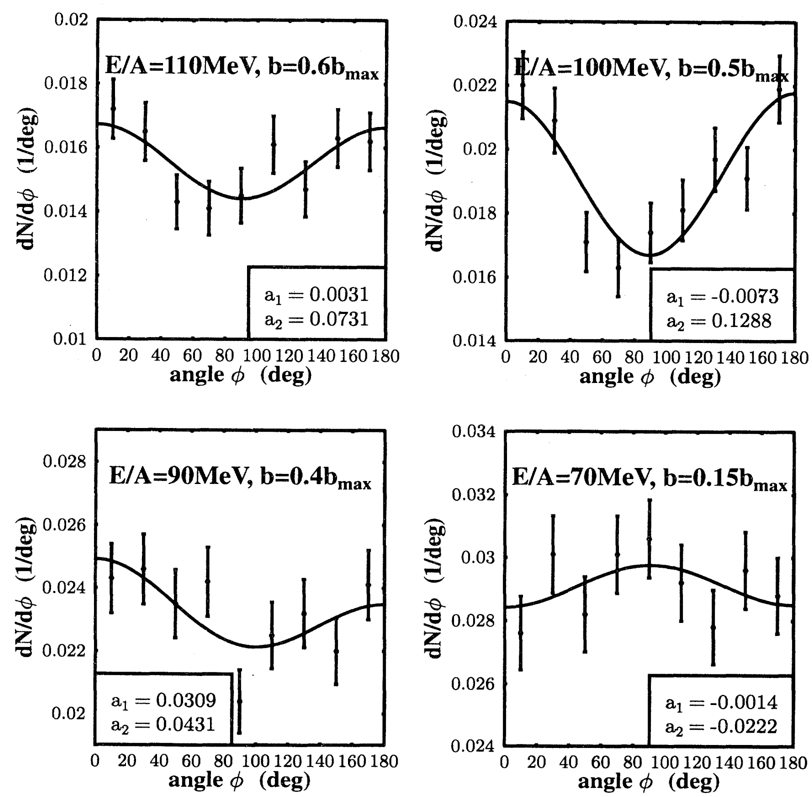

FIG. 6. Azimuthal distributions with respect to the reaction plane for Ca+Ca. The incident energies and impact parameters correspond to the determined in-plane balance energies $E_{\text{bal}}(b)$ with momentum-dependent interactions. The rapidity range is restricted to $-0.15 \leq y/y_p \leq 0.15$. The curves are fits according to $dN/d\phi = a_0[1 + a_1\cos(\phi) + a_2\cos(2\phi)]$.

dence of the reduced flow at the point where the reduced flow passes through zero (Fig. 2). One thousand events of Ca+Ca are performed for a hard equation of state without momentum-dependent interactions. Different symbols correspond to the different impact parameters $0.25b_{\rm max}, 0.4b_{\rm max}, 0.5b_{\rm max}, 0.6b_{\rm max}$. The balance energies differ completely for the different impact parameters. This is in contrast to claims in [36]. The errors of the balance energies are approximately $\pm 5A$ MeV.

Figure 3 depicts the impact parameter dependence of the balance energy for the system Ca+Ca. An approximate linear increase of the balance energy with impact parameter is visible. At larger impact parameters fewer nucleon-nucleon collisions yield reduced repulsive forces; therefore, the attractive mean field dominates. For larger impact parameters the balance energy is smaller if momentum dependent interactions (MDI's) are included, due to their repulsive effects. The balance energy is insensitive to the inclusion of MDI's for small impact parameters $b \le 0.4b_{\rm max}$. The balance energy for Ca+Ca varies from $65A$ to $150A$ MeV without MDI's and from $75A$ to $115A$ MeV with MDI's, depending on impact parameter. Experiments [7] show the balance energy for Ar+Sc, i.e., $A = 85$, to be $87 \pm 12A$ MeV, the impact parameter was estimated to be approximately $0.4b_{\rm max} \approx 3$ fm. This value is compatible with ours. Even for rather central collisions with a maximum impact parameter of $0.4b_{\rm max}$ the balance energies for Ca+Ca reach values from $65A$ MeV up to $95A$ MeV depending on the impact parameter. This is a significant variation contrary to the claims in [36]. A precise knowledge of the impact parameter is of utmost importance before any conclusions about the balance energy concern the equation of state or the in-medium nucleon-nucleon cross section.

Let us now turn to the two flow components showing both positive and negative flow in one event. Figure 4 illustrates this effect in semiperipheral collisions of Ca+Ca at $b = 0.85b_{\rm max} \approx 6.5$ fm and $E = 350A$ MeV. The nucleons show positive p_x values near midrapidity ($y_{\rm c.m.} \ge 0$) whereas negative p_x values are observed for the fragments at higher rapidities. The fragments are calculated in a simple configuration-space coalescence model [21]. Protons yield the major part of the component at midrapidity whereas heavier fragments rule the high-$y_{\rm c.m.}$ component. The time evolution of the collision can thus be imagined as if the spectators were attracted towards the participant zone.

The calculation is done for the hard equation of state without momentum-dependent interactions. It is very sensitive to the incident energy, the impact parameter, and to the addition of momentum dependent interactions.

The signs of the average p_x values become positive for all positive rapidities if the impact parameter is reduced to $b = 0.7b_{\rm max}$. The same happens if momentum-dependent interactions (which give additional repulsion) are introduced. The following scenario might explain the two components: Nucleons which have experienced higher densities, e.g., $\rho_{\rm max} \ge 1.3\rho_0$, are preferentially visible at small rapidities. This compressed, stopped matter shows positive flow. The spectator matter, which has experienced less compression, shows negative flow. The separation of the two components is clearly visible when applying a cut on the maximum density for slightly different system parameters ($E = 330A$ MeV and $b = 0.75b_{\rm max}$). Two-component flow is also observed with momentum-dependent interactions, e.g., for Ca+Ca at $170A$ MeV and $b = 0.8b_{\rm max}$.

Let us now turn to another point: A smaller balance energy $E_{\rm bal}$ is expected for the heavy system Au+Au ($A = 394$) than for Ca+Ca due to the cited $A^{-\frac{1}{3}}$ law. Experimentally so far only an upper bound for the balance energy of $E_{\rm bal} \le 60A$ MeV [12] has been found. Therefore the existence of negative flow is an open question due to the strong Coulomb repulsion. We show that this is

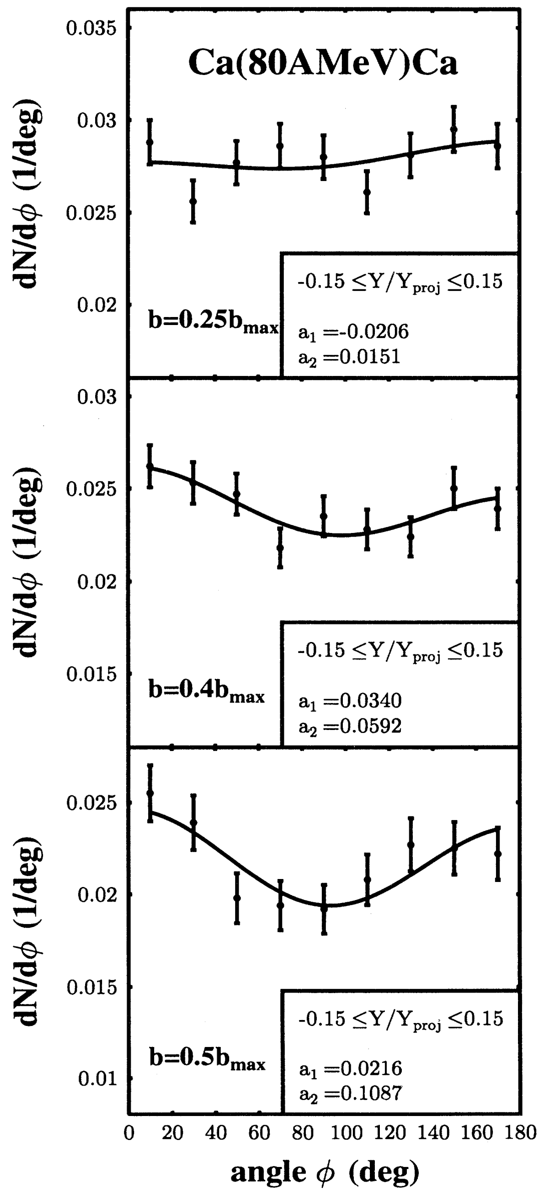

FIG. 7. Azimuthal distributions with respect to the reaction plane for Ca+Ca at $80A$ MeV and for three different impact parameters $b = 0.25b_{\rm max}$, $0.4b_{\rm max}$, and $0.5b_{\rm max}$.

due to an ill-defined frame of reference. The flow is in fact balanced at $E_{\rm bal} = (55 \pm 5)A$ MeV and $E_{\rm bal} = (65 \pm 5)A$ MeV for the impact parameters $b = 0.25b_{\rm max} \approx 3.3$ fm and $b = 0.5b_{\rm max} \approx 6.5$ fm, respectively, and for a hard equation of state without momentum-dependent interactions. These values are obtained if the initial precontact rotation of the system due to Rutherford trajectories is subtracted. In this system the sign reversal for the reduced flow is clearly visible. Figure 5 shows the respective calculation for Au+Au at $50A$ MeV and $b = 0.5b_{\rm max} \approx 6.5$ fm. In the rotated system the flow is obviously negative whereas a flat distribution is obtained in the laboratory frame. In the laboratory frame negative flow does not appear for any impact parameter, even not for low energies.

Let us now turn to the squeeze-out which is an established effect [37–39]. Excited participant matter is pushed out perpendicular to the reaction plane. At the energies dicussed in this paper this behavior might be different. In Fig. 6 these azimuthal angular distributions are plotted for the system Ca+Ca (hard EOS+MDI's) at their respective balance energies with different impact parameters. The considered rapidity is $-0.15 \leq y/y_p \leq 0.15$ according to recent experiments for the heavier system Zn+Ni [40]. The solid lines are the result of fits by the Legendre expansion: $dN/d\phi = a_0[1 + a_1\cos(\phi) + a_2\cos(2\phi)]$. The value of a_2 gives a measure of the anisotropy of this collective motion. Negative values of a_2 show preferred emission perpendicular to the reaction plane whereas positive values describe an enhancement in the reaction plane. Figure 6 shows that for Ca+Ca the in-plane emission is preferred for larger impact parameters, and a slight out-of-plane enhancement is observed for rather central collisions at the balance energies and at midrapidity. The transition energy where the anisotropy parameter a_2 becomes zero, corresponding to an azimuthally symmetrical distribution, was measured for Zn+Ni [40]. It was found that this transition energy is smaller than the corresponding balance energy. Our calculations for the lighter system Ca+Ca show the transition energies to be larger than the balance energy for larger impact parameter ($b \geq 0.4b_{\rm max}$), but smaller for more central collisions. This was already indicated by measurements for Ar+V [41]. Measurements indicate that the in-plane enhancement increases with impact parameter [42]. This can be seen in Fig. 7 for Ca+Ca at $80A$ MeV and various impact parameters. Light fragments show a slightly more pronounced in-plane to out-of-plane ratio than single nucleons if clustering is taken into account. Consequently, it must be pointed out that even at the in-plane balance energy collective flow characteristics are clearly visible in the azimuthal distributions.

IV. CONCLUSIONS

We have investigated the disappearance of the in-plane flow for Ca+Ca and Au+Au.

(i) A strong impact parameter dependence of the in-plane balance energy $E_{\rm bal}$ is observed. The balance energy clearly increases with impact parameter. This cannot be neglected while pinning down basic properties of excited nuclear matter.

(ii) The balance energy is smaller with momentum-dependent interactions than without for large impact parameters. The difference might be a tool to get information about the proper parametrization of the momentum-dependent interactions.

(iii) Negative flow angles will not be visible in the laboratory frame for the heavy Au+Au system due to the long-range Coulomb forces, although the in-plane flow disappears. Negative flow and the respective balance energies are visible in the frame where the precontact rotation due to the initial Rutherford trajectories is subtracted. However, a maximum mass must exist where negative flow can still be observed in the laboratory frame.

(iv) A new two-component flow was shown for large impact parameters. One component stems from participant particles at rapidities around $y_{\rm c.m.}$ whereas the other component results from cold spectator matter. They show opposite sign in the $p_x(y)$ distribution. The existence of two distinctly different flow components depends on the inclusion of momentum-dependent interactions. This is of great importance for the proper determination of the parametrization of the momentum-dependent interactions or other basic properties such as the in-medium NN cross section.

(v) Finally, azimuthal distributions demonstrate the existence of flow, even at the balance energy. For the system Ca+Ca the energy of the change from a preferentially in-plane to out-of-plane emission is smaller for central collisions and larger for increasing impact parameters than the balance energy. This energy of an azimuthally symmetrical distribution can provide valuable information complementary to the in-plane balance energy. The in-plane to out-of-plane ratio increases with impact parameter.

The search for tools to describe excited nuclear matter in nucleus-nucleus collisions and the search for signals to determine unambigiously the basic physical attributes is going on.

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