Is the existence of a softest point in the directed flow excitation function an unambiguous signal for the creation of a quark-gluon plasma?

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The excitation function of the in-plane directed flow of nucleons is studied within a non-equilibrium transport approach. It is demonstrated that a local minimum in the excitation function of the directed flow develops, which is not related to a transition into a quark-gluon plasma (QGP) phase. It is a consequence of the dynamical softening of the underlying equation of state, due to the onset of resonance matter and particle production. Thus, the interpretation of this minimum as a 'smoking gun' signature for the creation of a QGP is premature.

The excitation functions of hadron ratios and hadron flow has since long been suggested to search for evidence of exotic states and phase transitions in nuclear collisions [13].

Especially the in-plane collective flow is the earliest predicted observable to probe heated and compressed nuclear matter [1]. Its sensitivity to the equation of state (EoS) might be used to search for abnormal matter states and phase transitions [14]. Until now, the study of in-plane and azimuthal flow in high energy nuclear collisions is attracting large attention from both experimentalists and theorists [15,16].

In fluid dynamics, the transverse collective flow is intimately connected to the pressure \( P(\rho, S) \) (which in turn depends on the density \( \rho \) and the entropy \( S \)) of the matter in the reaction zone [17]:

\[
\mathbf{p} \propto \int_t \int_A P(\rho, S) \, dA \, dt.
\]

Here \( dA \) represents the surface element between the participant and spectator matters and the total pressure is the sum of the potential pressure and the kinetic pressure, while \( t \) denotes the time over which the pressure acts. Thus, the transverse collective flow depends directly on the equation of state, \( P(\rho, S) \).

The sensitivity of the flow on the equation of state [1,2,17,18] which governs the evolution of the system created in violent nucleus-nucleus collisions is conveniently addressed in terms of Fourier coefficients \( v_i \) of the azimuthal distribution (given by the angle \( \phi \)) of the explored hadrons. At fixed rapidity on expands:

\[
\frac{dN}{d\phi} = 1 + 2 v_1 \cos(\phi) + 2 v_2 \cos(2\phi),
\]

with

\[
v_1 = \left\langle \frac{p_x}{\sqrt{p_x^2 + p_y^2}} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle.
\]

The first coefficient describes the directed in-plane flow. The directed flow is most pronounced in semi-central interactions around target and projectile rapidities where the spectators are deflected away from the beam axis due to a bounce-off from the compressed and heated matter in the overlap region. The time scales probed by the directed flow are set by the crossing time of the Lorentz-contrasted nuclei. Thus, it serves as key-hole to the initial, probably non-equilibrium, stage of the reaction.

In contrast, the elliptic flow \([12,17,24]\) as measured by the \( v_2 \) coefficient is generated after the overlap of the initial nuclei. This type of flow is strongest around central rapidities in semi-peripheral collisions. It is driven by the anisotropy of the pressure gradients, due to the geometry of the initial overlap region. Therefore, it is a valuable tool to gain insight into the expansion stage of the fireball.

Both types of flow can be used to investigate the so-called 'softest point' - i.e. a local minimum of \( P/\epsilon \) as a function of the energy density \( \epsilon \) - in the EoS [20]. As pointed out in [20,21], the existence of this 'softest point' leads to a prolonged expansion of matter and consequently to a long lifetime of a mixed phase of QGP and hadron matter. Analogously, it also takes longer to compress matter in the early stage of a heavy-ion collision [28]. These features result in two key predictions as 'smoking gun' signatures for Quark-Gluon-Plasma formation:

- A kinked centrality dependence of the scaled elliptic flow [20] and
- a minimum in the excitation function of the directed in-plane collective flow [1].

Especially, the observation of this local minimum in the energy dependence of the in-plane directed flow

\[
p_x^{\text{dir}} = \frac{1}{M} \sum_{i} p_x i \, \text{sgn}(y_i)
\]

in heavy-ion collisions - here \( i \) sums over all considered nucleons, \( p_x i \) is the momentum in \( x \) direction of nucleon \( i \) and \( y_i \) denotes the rapidity of nucleon \( i \) - has been suggested to be a clear signature for a change of nuclear
matter properties as for instance in the transition from hadron to quark and gluon degrees of freedom (see also the pioneering works by Refs. [33, 34]).

Recently, a more complex dynamical picture behind the softening of the directed flow had been discovered. In Refs. [22] and [32] it was argued that in case of a QGP creation at first strong directed flow develops, which is later compensated by an anti-flow of nucleons at central rapidities.

In this letter, we study the excitation function of the directed flow and its connection to the underlying equation of state. We demonstrate that the common interpretation of the softening of the equation of state as a unique signature of a mixed phase near a transition to a QGP is premature.

For our investigation, the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD 1.2) [35] is applied to heavy ion reactions from $E_{\text{beam}} = 100$ AMeV to 500 AGeV. This microscopic transport approach is based on the covariant propagation of constituent quarks and diquarks accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of ingoing and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. Towards higher energies, the treatment of sub-hadronic degrees of freedom is of major importance. In the present model, these degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [34, 36]. The leading hadrons of the fragmenting strings contain the valence-quarks of the original excited hadron. In UrQMD they are allowed to interact even during their formation time, with a reduced cross section defined by the additive quark model, thus accounting for the original valence quarks contained in that hadron [35]. A phase transition to a quark-gluon state is not incorporated explicitly into the model dynamics. However, a detailed analysis of the model in equilibrium yields an effective equation of state of Hagedorn type [37-38].

Note that the present simulations have been performed without potential interactions. Thus the absolute magnitude of the directed flow at the lowest energies is certainly underpredicted [34]. Nevertheless, the general statement of a non-monotonic dependence of the directed flow on the collision energy is not blurred by this detail.

As a measure for particle production, we define an inelasticity:

$$\text{Inelasticity} = \sum \frac{m_i}{E_{\text{total}}} \text{ at } y_{\text{cm}} \pm 0.5 , \quad (5)$$

the sum is taken over all newly produced particles, with $m_i$ being the mass of each produced particle and $E_{\text{total}}$ being the total available energy, $E_{\text{total}} = A\sqrt{s}$, for a given center-of-mass energy $\sqrt{s}$.

Fig. 1 depicts the excitation functions of the directed flow of protons (full squares) and the inelasticity (open triangles) for central Au+Au (Pb+Pb) reactions with $b \leq 3.4$ fm. One clearly observes a non-monotonic behavior of the directed flow excitation function from UrQMD: Up to 1 AGeV beam energy the directed flow of nucleons increases. As particle production sets in, the directed flow starts to decrease and a prominent dip occurs at 8 AGeV beam energy. The development of the dip in $p_{\text{dir}}^x$ is directly connected to the onset of particle production, as measured by the inelasticity. At 15 AGeV beam energy, the inelasticity decreases again and the directed flow increases until a beam energy of 40 AGeV. From there on, $p_{\text{dir}}^x$ stays constant towards the top SPS energy.

For comparison, simulations with an energy independent elastic and isotropic nucleon-nucleon cross section of 40 mb are shown in Fig. 1 (open squares). Here one clearly observes a strong and monotonous increase of the directed flow with energy.

While both approaches, hydrodynamics with a phase transition to a QGP or the dynamical softening of the EoS presented here, do yield a minimum in the flow excitation function, the time evolution of the flow pattern is different. In scenarios with QGP phase transition, the development of a nucleonic anti-flow is visible in the time evolution of the directed flow: with QGP, the directed
flow at the softest point increases in the early stage of the collision, but then suddenly turns over and decreases as the anti-flow sets in \[22,32\]. In Fig. 2 the time evolution of the directed flow is studied in the transport model. Here, the directed flow increases monotonously with time until its final saturation value. In both studied scenarios, i.e. with the full collision term included (full squares) and in the simulation with only elastic collisions (open squares), no local maximum in the time evolution of $p_t^{dir}$ is present. Investigating the directed flow at midrapidity shows that in the present model, the minimum in the directed flow is not due to a counter-acting anti-flow of nucleons at central rapidities as discussed in \[22,32\].

Thus, the observation or non-observation of the anti-flow of nucleons near central rapidities is crucial to distinguish hadronic dynamics from QGP formation. Unfortunately, up to now all flow measurements at relativistic energies cover only the range outside $y/y_{cm} \pm 0.3$ \[32\].

The quantitative value and the sign of the flow near midrapidity remains undetermined. Additional information about the origin of the softening of the EoS might also be obtained by studying the variation of the scaled elliptic flow with centrality at fixed energy \[23\]. The low energy runs of the NA49 experiment (beam energies of 20 AGeV, 30 AGeV and 40 AGeV) might be able to explore these phenomena in detail \[10\]. The softening of the equation of state, and the minimum of the directed flow will also be accessible by the future GSI accelerator \[11\].

In summary, we have demonstrated that a string hadronic model is able to yield a non-monotonic directed flow excitation function. In the present model this is due to a dynamical change (softening) of the equation of state due to a transition to resonance rich matter in line, with the onset of particle production. Irrespective of quantitative uncertainties, we conclude that a minimum in the $p_t^{dir}$ excitation function is not a clean signal for a transition from hadron to parton matter in nuclear collisions.

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