Directed flow in heavy-ion collisions at NICA: what is interesting to measure?

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Abstract. We study the formation of the directed flow of hadrons in nuclear collisions at energies between AGS and SPS in Monte Carlo cascade model. The slope of the proton flow at midrapidity tends to zero (softening) with increasing impact parameter of the collision. For very peripheral topologies this slope becomes negative (antiflow). The effect is caused by rescattering of hadrons in remnants of the colliding nuclei. Since the softening of the proton flow can be misinterpreted as indication of the presence of quark-gluon plasma, we propose several measurements at NICA facility which can help one to distinguish between the cases with and without the plasma formation.

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1 Introduction

The collective flow of hadrons, produced in the course of nuclear collisions at (ultra)relativistic energies, was found already quite long ago to be able to carry information about the energy density, pressure, compressibility, etc. of the medium \textsuperscript{[1234]}. Therefore, the flow was suggested as a good messenger of a new state state of matter - the quark-gluon plasma (QGP). At that time the anisotropic flow, appeared in non-central collisions, was subdivided into two components \textsuperscript{[45]}, namely the in-plane flow, elongated within the reaction plane and called bounce-off or directed flow, and the out-of-plane flow, orthogonal to the reaction plane and known as side-splash or squeeze-out flow. The side-splash of the participants and the bounce-off of the spectators were first detected by the Plastic Ball collaboration \textsuperscript{[6]} at Bevalac (Berkeley). The measured average in-plane transverse momentum per nucleon, \( \langle p_x(y)/A \rangle \), is found to have a characteristic \( S \)-shape as a function of centrality. Its magnitude increases with rising projectile/target mass and reaches a maximum in semi-central collisions \textsuperscript{[3]}. Both bounce-off and squeeze-out flows become stronger in the case of heavy fragments \textsuperscript{[7]}, which have relatively small undirected thermal velocities.

Note that at energies \( E_{lab} \) below few GeV the fraction of nucleons heavily dominates the spectrum of hadrons. It was found that the proton flow had a linear slope at midrapidity, and the scaling behaviour was observed, see \textsuperscript{[8]} and references therein. - If one normalises the proton momentum \( p_x \) and rapidity \( y \) to the projectile center-of-mass momentum \( p_{proj} \) and rapidity \( y_{proj} \), respectively, and then determines the slope of the proton flow at midrapidity

\[
F = \left. \frac{\partial \langle \tilde{p}_x(y) \rangle}{\partial \tilde{y}} \right|_{\tilde{y}=0},
\]

where \( \tilde{p}_x = p_x/p_{proj} \) and \( \tilde{y} = y/y_{proj} \), the reduced slopes \( \tilde{F} = F/p_{proj} \) appear to sit on the top of each other, thus revealing the scaling \textsuperscript{[8]}. Violation of this scaling at collision energies of AGS and higher was predicted by one of the authors in \textsuperscript{[9]}. Its origin will be discussed in detail in Sect. \textsuperscript{3}.

The new era in the investigation of collective anisotropic flow of hadrons began about 20 years ago, when the Fourier decomposition of the azimuthal distribution of hadrons was proposed \textsuperscript{[10]}

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \Psi_n)].
\]

Here \( \phi \) and \( \Psi_n \) denote the azimuthal angle between the particle transverse momentum and the participant event plane, and the azimuth of the event plane of \( n \)th flow component, respectively. The Fourier coefficients \( v_n \) are the flow harmonics,

\[
v_n = \langle \cos [n(\phi - \Psi_n)] \rangle,
\]

which can be found after the averaging over all particles and all events. Nowadays the first coefficients are colloquially known as directed, \( v_1 \), elliptic, \( v_2 \), triangular, \( v_3 \), flow,
and so forth. It appears that the directed flow is still elongated in the reaction plane. However, in contrast to the former directed/bounce-off flow, $v_1$ is not just averaged projection of particle momentum on the impact parameter axis but rather its averaged ratio to the transverse momentum, $v_1 = (p_t / p_T)$. Nonetheless it is clear that, apart from the magnitude of the signal, the basic features of the behaviour of former bounce-off and modern directed flow must be similar.

In case of the first order phase transition between the QGP and the hadronic matter, the disappearance of the pressure gradients in the mixed plasma-hadrons phase should lead to the softest point of the equation of state [11]. Such a softening will be clearly seen in the excitation function of the directed flow [12-13]. The STAR Collaboration has found during the beam energy scan (BES) at RHIC that the slope of the proton flow at midrapidity changes from sign to positive between 7.7 and 11.5 GeV [14]. After reaching a local minimum between 11.5 and 19.6 GeV, the slope tends to zero, though remains negative, with rising energy of the collision. Several models have tried to describe these observations by invoking the hypothesis of a crossover type of quark-hadron phase transition [15-16].

In the present paper we argue that such a signal can be obtained by means of Monte Carlo cascade model, at least at a qualitative level. In Sect. 3, therefore, we present several features and tendencies in the development of hadronic directed flow which are characteristic for the microscopic transport models. Various measurable signals are proposed to discriminate between the QGP state and pure hadronic states. We start from the short description of basic principles of the quark-gluon string model (QGSM) which is used for the calculations.

2 Quark-gluon string model

The quark-gluon string model (QGSM) [17,18,19,20] is a Monte Carlo cascade model which utilizes the Gribov Reggeon field theory (RFT) [21,22] and string phenomenology. It relies on the so-called topological $1/N_c$ expansion [23] in quantum chromodynamics (QCD), where $N_c$ is the number of colours. For semi-hard hadronic collisions the perturbative QCD methods are employed [24]. The model is similar to the dual parton model (DPM) [25] and the VENUS model [26]. It neglects the potential interactions between hadrons and concentrates on hadronic rescattering. QGSM takes into account (i) the processes with quark exchange and with quark annihilation, corresponding to Reggeon exchanges in GRT, (ii) the processes with colour exchange, corresponding to the Pomeron exchanges, (iii) single and double diffraction processes, (iv) elastic scattering, (v) baryon-antibaryon annihilation, and (vi) hard gluon-glue scattering with large momentum transfer. The model considers secondary interactions of the produced hadrons with the spectators and with the produced hadrons, as well as between some unformed ones (string-string interaction), based on the hadron formation time. It provides a fair description of the global characteristics of $hh$, $hA$ and $A+A$ collisions at AGS and SPS energies.

Although QGSM has no explicit assumption on the QGP formation, a lot of intermediate hadronic objects - strings - are formed during the initial stage of the collision. The strings absorb an essential part of energy and baryon charge, thus these energetic non-hadronic objects could be considered as non-equilibrated precursors of the QGP phase. Further details of the model can be found in [17,18,19,20]. Directed flow of hadrons in heavy-ion collisions at energies from AGS ($E_{lab}=11.6$ AGeV) and up to RHIC ($\sqrt{s_{NN}}=200$ GeV) was studied within the QGSM in Refs. [1,21,22,28,29,30,31,32,33,34]. Many of the features in the development of the directed flow are not attributed solely to QGSM but are common for a wide class of MC cascade models. Let us discuss them.

3 Directed flow in QGSM

3.1 Softening of nucleon directed flow at midrapidity

For better understanding of this phenomenon we choose collisions of light ($^{32}$S + $^{32}$S) and heavy ($^{197}$Au + $^{197}$Au) nuclei. The comparison between the systems is done in terms of the reduced impact parameter $b/b_{\text{max}}$, where maximal impact parameter is equal to nuclear diameter, $b_{\text{max}} = 2R_A$, and reduced rapidity $y/y_{\text{proj}}$. Results for $v_1(y)$ distributions of nucleons and pions are shown in Fig. 1(a,b) for six centrality bins from $b = 0.15$ to $b = 0.90$. For light system the slope of $v_1(y)$ at midrapidity becomes not so steep already at $b = 0.3$. The nucleon directed flow decreases with rising $b$, and in peripheral collisions at $b \geq 0.7$ it develops the antiflow similar to that of the pions. - Conventionally, we call the direction of the directed flow normal if the product $p_x y$ is positive, $p_x y > 0$, and antiflow if $p_x y < 0$. - The pion directed flow always demonstrates the antiflow behaviour. For heavy system the flatness of $v_1(y)$ at midrapidity accompanied by the transition to antiflow seems to build up at $b \geq 0.7$ only. With increasing energy of the collision, however, this limit is shifted towards more central topologies [29-31].

The reduction of the directed flow can be interpreted as softening of the EOS because of the QGP-hadrons phase transition [11,13]. One may also think about the colour field of the strings, which can lead to softening of hadronic EOS and thus imitate the plasma formation. This hypothesis fails to explain why the effect of the $v_1$ disappearance is stronger (i) in collisions of light ions and (ii) in peripheral collisions compared to the semi-central ones. The most reliable explanation of this phenomenon is the shadowing (or screening) of emitted hadrons by the spectators.

To illustrate this idea we display in Fig. 2 a snapshot of collective velocities and baryon densities of the rectangular cells with volumes $V \approx 3$ fm$^3$ in S+S collisions at SPS energy. The impact parameter is fixed at $b = 2.13$ fm corresponding to $b = 0.3$, and the snapshot is taken at $t = 6$ fm/$c$ after beginning of the collision. The cells which
develop normal flow always follow the baryon-rich spectator zones, whereas the antiflow is developed in more dilute areas. Hadrons with small rapidities, emitted early in the direction of normal flow, will be absorbed by flying spectators. These particles should get higher rapidities after a sequence of rescatterings. If the collision energy increases to that of RHIC or LHC, more hadrons are produced and the remnants of the nuclei leave the interaction zone much quicker, thus giving space for the development of flow in both directions. Directed flow at midrapidity will drop almost to zero, in agreement with the experimental observations \[35\]. If the collision energy is the same, but instead of the light system collision of heavy ions takes place, then the number of produced hadrons increases. Here absorption of the early emitted hadrons by the spectators takes place as well, but this process becomes less efficient compared to that of the light system, where the isotropic particle radiation from the central part is not so strong. Therefore, the directed flow for heavy-ion systems displays softening in more peripheral collisions. At bombarding energies below 1-2 GeV the directed flow of hadrons is dominated by the participant nucleons. The flow has a characteristic S-shape and is stronger in heavier systems. Energies accessible for NICA lie in a very interesting region, where transition from baryon-dominated matter to meson-dominated one takes place. Recall, that at \(E_{\text{lab}} \approx 40\) AGeV fractions of baryons and mesons in heavy-ion collisions are about the same. Somewhere here the antiflow of protons at midrapidity reaches its maximum, whereas in the fragmentation regions the \(v_p^1(y)\) turns back to normal flow behaviour. Therefore, it is important to measure not only the midrapidity range \(|y| \leq 1\), but also the areas of target and projectile fragmentation. Needless to say, that both central and peripheral collisions up to 80% or more should be measured.

### 3.2 Directed flow of high-\(p_T\) hadrons

This issue is also very interesting, and NICA’s energy range suits well for the study. First, let us present what was observed in the model calculations \[31,32\]. Here the
directed flow of high- 
particularly in transverse momentum intervals
\[ v_1(y, \Delta p_T) = \frac{\int_{p_T^{(1)}}^{p_T^{(2)}} \cos(n\Delta \phi) \frac{d^2N}{dp_T^2 dy} dp_T^2}{\int_{p_T^{(1)}}^{p_T^{(2)}} \frac{d^2N}{dp_T^2 dy} dp_T^2} . \] 

It was found that the directed flow of nucleons in peripheral collisions changed the slope at midrapidity from anti-flow to normal flow provided the nucleons with transverse momenta \( p_T \geq 0.6 \text{ GeV/c} \) were selected. In addition, even directed flow of high-\( p_T \) pions and kaons changed its sign and became positive. In microscopic model this peculiarity is explained by early emission times of high-\( p_T \) particles. There is no sharp particle freeze-out in microscopic models, and hadrons are emitted continuously from the interaction zone albeit with different production rates \[36\]. At both AGS and SPS energies nucleons with highest transverse momenta are coming either from the initial nucleus (fireball). Pions in Au+Au collisions at AGS demonstrate the same tendency \[36\], whereas the pions with highest \( p_T \) in the reactions at energies of SPS or higher are produced only within the first 1-2 fm/c \[37\] in primary inelastic nucleon-nucleon collisions. These pions carry normal directed flow.

In experiments, the sign flip of the directed flow of high-\( p_T \) pions was observed in heavy-ion collisions at SIS (1 AGeV) \[38\], AGS \[39,40\], and SPS \[41\] energies. In line with the microscopic calculations, the effect was found to be stronger in peripheral collisions and at higher rapidities. Since the formation of rapidly expanding thermal source in light-ion collisions or in peripheral heavy-ion collisions is less likely compared to more central heavy-ion collisions, the most plausible explanation of the effect is screening/shadowing by the remnants of the spectators. Note also, that at SIS energies pions with high \( p_T \) are emitted within the first 15-20 fm/c of the collision \[42,43\]. These pions experience at least 2-3 quasi-elastic scattering with nucleons, which lead to the partial thermalization of their spectrum and, therefore, to possibility of their usage as a “time-clock” for probing the high-density phase. At SPS energies this option is quite doubtful. Thus, the freeze-out of hadron species at NICA deserves further investigations.

\[ 4 \text{ Conclusions} \]

The microscopic cascade model allows for reduction and changing the sign of the slope of directed flow of protons in (semi)peripheral nuclear collisions at relativistic energies. This effect can emulate the expected vanishing of the directed flow because of the phase transition from QGP to hadrons, which causes the softening of the equation of state. In case of the QGP formation the softening of the directed flow should be stronger in semi-central collisions and in collisions of heavy ions compared to the light-ion ones. If the effect is caused by hadron interactions in baryon-rich remnants of the colliding nuclei, the result should be opposite. To distinguish between the two phenomena, one can carry the following measurements at NICA facility:

- perform a run with light nuclei, say Cu+Cu or lighter. Results of the flow measurements in heavy-ion and light-ion systems should be compared in terms of reduced impact parameter \( \hat{b} = b/2RA \) and reduced rapidity \( \hat{y} = y/y_{proj} \);
- measurement of directed flow in both central and peripheral events (up to 90% of centrality);
- measurement of particle \( v_1 \) not only at midrapidity but also in the region of target/projectile fragmentation;
- determination of directed flow of hadrons with high, or even highest, transverse momenta.

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