Directed flow in heavy-ion collisions from the PHSD transport approach

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Abstract. Recent STAR data for the directed flow of protons, antiprotons, charged pions and kaons obtained within the beam energy scan (BES) program are analyzed within the Parton-Hadron-String-Dynamics (PHSD/HSD) transport models. Both versions of the kinetic approach are used to clarify the role of partonic degrees of freedom. The PHSD results, simulating a partonic phase and its coexistence with a hadronic one, are roughly consistent with the STAR data. Generally, the semi-qualitative agreement between the measured data and model results supports the idea of a crossover type of quark-hadron transition which softens the nuclear EoS but shows no indication of a first-order phase transition. Furthermore, the directed flow of kaons and antikaons is evaluated in the PHSD approach from $\sqrt{s_{NN}} \approx 5 - 12$ GeV which shows a high sensitivity to the hadronic potentials in the FAIR/NICA energy regime $\sqrt{s_{NN}} \leq 8$ GeV.

High energy heavy-ion collisions are the unique experimental way to study the Equation of State (EoS) of strongly interacting matter. New experiments on this topic are currently in preparation such as the CBM at FAIR and the MPD at NICA. In order to extract information about the behaviour of matter, one has to analyse the data with respect to the production of various hadronic particles, both mesons and baryons. This analysis is highly non-trivial, since at these energy regimes, the baryon chemical potential cannot be neglected and, unfortunately, the EoS of the matter at finite baryon chemical potential is still quite uncertain. The possibility to investigate the deconfinement phase transition at high baryon density and moderate temperature is one of the main goals of the scientific community in the recent years. Since the QGP is created only for a short time (of a couple of fm/c) it is quite challenging to study its properties and to find the most sensible probes. The study of the particle azimuthal angular distribution in momentum space with respect to the reaction plane is an important tool to probe the hot, dense matter created in heavy-ion collisions [1]. The directed flow refers to a collective sidewards deflection of particles and is characterized by the first-order harmonic $v_1$ of the Fourier expansion of the particle azimuthal angular distribution with respect to the reaction plane [2]. Apart from first measurements in the early nineties and till recent times, the directed flow was studied mainly theoretically although some experimental information from the Schwerionen-Synchrotron (SIS) to Super-Proton-Synchrotron (SPS) energies is available [3]. It is generally assumed that the directed flow is generated during the nuclear passage time [4]. The directed transverse flow therefore probes the onset of bulk collective dynamics during thermalization, thus providing valuable information also on the pre-equilibrium stage.

The interest in the directed flow $v_1(y)$ has recently been enhanced considerably due to new STAR data obtained in the framework of the beam-energy-scan (BES) program [5]. The directed flow of identified hadrons – protons, antiprotons, positive and negative pions and more recently
also kaons and antikaons [6] – has been measured with high precision for semi-central Au+Au collisions in the energy range $\sqrt{s_{NN}} = (7.7-39)$ GeV. These data provide a promising basis for studying direct-flow issues as discussed above and have been addressed already by the Frankfurt group [7] limiting themselves to the energy $\sqrt{s_{NN}} < 20$ GeV where hadronic processes are expected to be dominant. However, the authors of Ref. [7] did not succeed to describe the data and to obtain conclusive results which led to the notion of the ‘directed flow puzzle’. Our study aims to analyze these STAR results in the whole available energy range including in particular antiproton and $K^{\pm}$ data [8, 9].

The description of the PHSD model employed here is described elsewhere [10, 11]. It involves dynamical partons with a scalar selfenergy, a covariant hadronization scheme as well as hadronic rescattering with (optionally) mean-field potentials. In the hadronic phase, i.e. for energies densities below the critical energy density $\epsilon_c \approx 0.5$ GeV/fm$^3$, the PHSD approach is identical to the Hadron-String-Dynamics (HSD) model [12, 13].

The directed flow $v_1(y) = \langle \cos(\psi - \Psi_{RP}) \rangle = \left\langle \frac{p_x}{\sqrt{p_x^2 + y^2}} \right\rangle$, (1)
is computed for all hadrons separately as a function of rapidity $y$ within the experimental momentum acceptance. The characteristic slope $F$ of the $v_1(y)$ distributions at midrapidity, $F := dv_1/dy|_{y=0}$, is presented in Fig. 1 (l.h.s.) for all cases considered. In fact, in a first approximation the $v_1$ flow in the center-of-mass system may be well fitted by a linear function $v_1(y) = F y$ within the rapidity interval $-0.5 < y < 0.5$. For protons there is a qualitative agreement of the HSD/PHSD results with the experiment measurements: the slope $F > 0$ at low energies, however, exceeding the experimental values by up a factor of about two; the slope crosses the line $F = 0$ at $\sqrt{s_{NN}} \sim 20$ GeV, which is twice larger than the experimental crossing point, and then stays negative and almost constant with further energy increase. However, the absolute values of the calculated proton slopes in this high energy range are on the level of -(0.010-0.015), while the measured ones are about -0.005. The standard UrQMD model results, as cited in the experimental paper [5] and in the more recent theoretical work [7], are displayed in Fig. 1 (l.h.s.) by the wide and narrow shaded areas, respectively. These results for protons are close to those from the HSD and essentially overestimate the slope for energies below $\sim 30$ GeV but at higher energy become negative and relatively close to the experiment. The predictions for the pure hadronic version of the transport model HSD (dotted lines in Fig. 1 (l.h.s.)) slightly differ from the PHSD results which overpredict the negative proton slope at higher RHIC energies.

For the antiproton slopes we again observe an almost quantitative agreement with the BES experiments [5]: with increasing collision energy the HSD and PHSD slopes grow and then flatten above 20-30 GeV. The HSD results saturate at $v_1(0) = 0$, while the PHSD predictions stay negative and in good agreement with experiment (see Fig. 1 (l.h.s.)). It is noteworthy to point out that these PHSD predictions strongly differ from the UrQMD results which no longer describe the data for $\sqrt{s_{NN}} \leq 20$ GeV but are in agreement with the measurements for higher energies.

The differences between the calculations and experimental data become apparent for the charged pion slopes at $\sqrt{s_{NN}} \leq 11$ GeV: the negative minimum of the charged pion slope is deeper than the measured one. The HSD and PHSD results practically coincide at low energy (due to a minor impact of partonic degrees-of-freedom) but dramatically differ from those of the UrQMD model for $\sqrt{s_{NN}} \leq 20$ GeV (see Fig.1 (l.h.s.)).

Thus, in agreement with the STAR experimental data, in the considered energy range the PHSD model predicts for protons a smooth $F(\sqrt{s_{NN}})$ function which is flattening at $\sqrt{s_{NN}} \geq 20$ GeV and reveals no signatures of a possible first-order phase transition as expected.
Figure 1. (l.h.s.) The beam energy dependence of the directed flow slope $F$ at midrapidity for protons, antiproton and charged pions from semicentral Au+Au collisions [8]. The shaded band corresponds to the UrQMD results as cited in [5]. The experimental data are from the STAR collaboration [5] along with results of prior experiments using comparable cuts. (r.h.s.) The directed flow slope $F$ for $K^+$, $K^-$, $K^0$ as a function of the invariant energy $\sqrt{s_{NN}}$ with (dashed purple lines) and without kaon potentials (solid blue lines) in the PHSD calculations.

Strange hadrons and in particular kaons and antikaons provide additional information on the reaction dynamics. In relativistic mean-field models the dispersion relation for kaons and antikaons in the nuclear medium can be written as [16, 17, 18]

$$\omega_{K\pm}^2(\rho_N, p) = \pm \frac{3}{4} \frac{\omega}{f_K^2} \rho_N + m_K^2 + p^2 \left( \frac{\Sigma_{KN}}{f_K} \right) \rho_s. \tag{2}$$

In Eq. (2) $\Sigma_{KN}$ is the kaon-nucleon sigma term ($\approx 400$ MeV), $m_K$ denotes the bare kaon mass, $f_K \approx 100$ MeV is the kaon decay constant, while $\rho_s$ and $\rho_N$ stand for the scalar and vector nucleon densities, respectively. This leads to repulsive kaon mean fields $U_K > 0$ and attractive mean fields for the antikaons $U_{\bar{K}} < 0$ at finite baryon density [16].
The microscopic calculation of kaon and antikaon potentials (or mean fields) is more involved and can e.g. be worked out within G-matrix theory [17, 18]. These calculations show that the potentials also explicitly depend on the $K^\pm$ momentum $p$ with respect to the local rest frame of the system. Such a momentum-dependence can be incorporated by introducing momentum dependent formfactors in the scalar and vector potentials and fitting the parameters to the results from G-matrix theory up to twice nuclear matter density. In order to shed some light on the possible effects of $K^\pm$ potentials on their directed flow - especially at FAIR/NICA energies - we have incorporated the momentum-dependent potentials for kaons and antikaons as displayed in Fig. 5 of Ref. [9].

We directly step on with the preliminary results for Au+Au collisions at impact parameters 6 to 9 fm for invariant energies of $\sqrt{s_{NN}}$ from 5 to 12 GeV, i.e. at the FAIR/NICA energies and the low RHIC energy. The actual results are shown in Fig. 1 (r.h.s.) for $K^+, K^-$ and $K^0$ mesons as a function of the invariant energy $\sqrt{s_{NN}}$ with (dashed purple lines) and without kaon potentials (solid blue lines) in the PHSD calculations. These directed flows are comparable in size with those from the pions. The focus in this case is on the role of the kaon/antikaon potentials. We find a remarkable sensitivity to the kaon/antikaon potentials in this low energy (FAIR/NICA) domain; the positive flow of kaons even changes sign when including the repulsive potentials, whereas the antikaon flow is decreased in size substantially by the attractive mean fields. The $K^0$ flow presents features similar to $K^+$, since they are associated with the same repulsive potential (except for Coulomb forces). Above $\sqrt{s_{NN}} \sim 12$ GeV there is no longer a sizeable sensitivity to the kaon/antikaon potentials. Comparing our results for $K^+, K^-$ with the data, we infer that the presently adopted kaon potential is too strong, while the antikaon potential is too soft.

We speculate that the inclusion of a restoration of chiral symmetry at high baryon density and/or temperature might lead to a solution of the currently remaining problems. Moreover, precise experimental studies at FAIR, NICA or within the BES II program at RHIC will provide more information on the kaon/antikaon potentials.

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