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Does non-monotonic behavior of directed flow signal the onset of deconfinement ?

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Abstract

We investigate the effects of nuclear mean-field as well as the formation and decay of nuclear clusters on the directed flow v_1 in high energy nucleus-nucleus collisions from $\sqrt{s_{NN}} = 7.7$ GeV to 27 GeV incident energies within a transport model. Specifically, we use the JAM transport model in which potentials are implemented based on the framework of the relativistic quantum molecular dynamics. Our approach reproduces the rapidity dependence of directed flow data up to $\sqrt{s_{NN}} \approx 8$ GeV showing the significant importance of mean-field. However, the slopes of dv_1/dy at mid-rapidity are calculated to be positive at $\sqrt{s_{NN}} = 11.7$ and 19.6 GeV, and becomes negative above 27 GeV. Thus the result from the JAM hadronic transport model with nuclear mean-field approach is incompatible with the data. Therefore within our approach, we conclude that the excitation function of the directed flow cannot be explained by the hadronic degree of freedom alone.

Keywords: relativistic heavy-ion collisions, quark-gluon plasma, transport approach

1. Introduction

Determination of the equation of state (EoS) at high density QCD matter from an anisotropic flow in heavy ion collisions has been discussed for a long time. In particular, the softening of the EoS influences drastically the nucleon directed flow, and collapse of the directed flow $v_1 = \langle \cos\phi \rangle$ has been suggested as a signal of the phase transition from ordinary hadronic matter to quark-gluon plasma (QGP) [1, 2]. The slope of nucleon v_1 is normally positive in the hadronic scenario, but hydrodynamical calculations with QGP EoS predict a negative slope of v_1 at mid-rapidity, when matter passes through the softest point of the EoS [3, 4]. On the other hand, microscopic hadronic transport calculations also yield a negative slope due to geometrical effects at sufficiently high collision energies [5, 6]. The theoretical studies on the beam energy dependence of the directed flow based on the newly developed models such as hybrid transport approach [7], three fluid model [8], and the PHDS transport model [9] have been extensively performed. However, a definite conclusion has not been drawn so far as to the interpretation of the directed flow data measured by the STAR collaboration [10].

In this work, we compute beam energy dependence of the directed flow in the energy range of the beam energy scan (BES) program at RHIC within a hadronic transport model in which baryon mean-field is implemented within the formalism of the simplified version of the relativistic quantum molecular dynamics. The effects of nuclear cluster formations and their statistical decay on the spectra are also investigated.

2. Hadronic trasport model

We employ a hadronic transport model JAM that has been developed based on the resonance and string degrees of freedom [11]. Particle productions are modeled by the resonance or string excitations and their decays. Secondary interactions among produced particles are also included via the two-body collision. Nuclear mean-field of baryons are included based on the framework of a simplified version of relativistic quantum molecular dynamics (RQMD/S) [12]. We adopt the following Skyrme-type density dependent and Lorentzian-type momentum dependent mean field potential for baryons,

$$U(\boldsymbol{r},\boldsymbol{p}) = \alpha\left(\frac{\rho(\boldsymbol{r})}{\rho_0}\right) + \beta\left(\frac{\rho(\boldsymbol{r})}{\rho_0}\right)^{\gamma} + \sum_k \frac{C_k}{\rho_0}\int d\boldsymbol{p}'\frac{f(\boldsymbol{r},\boldsymbol{p}')}{1+[(\boldsymbol{p}-\boldsymbol{p}')/\mu_k]^2}\ , \tag{1}$$

where $f(\boldsymbol{r},\boldsymbol{p})$ is the phase space distribution function, and its integral over $\boldsymbol{p}$ becomes the density distribution $\rho(\boldsymbol{r})$. In RQMD/S, $\rho(\boldsymbol{r})$ is computed by assuming Gaussian distribution function. We use the parameter set which yields the incompressibility of $K = 272$ MeV; $\alpha = -0.209$ GeV, $\beta = 0.284$ GeV, $\gamma = 7/6$, $\mu_1 = 2.02$ fm^{-1}, $\mu_2 = 1.0$ fm^{-1}, $C_1 = -0.383$ GeV, $C_2 = 0.337$ GeV, and $\rho_0 = 0.168$ fm^{-3}.

The formation of nuclear clusters are taken into account based on the phase space distribution of nucleons at the end of the simulation. If nucleons are close in the phase space, nuclear cluster is formed: if the relative distances and momenta between nucleons are less than R_0 and P_0 at the same time, these nucleons are considered to belong to the same nuclear cluster. Coalescence parameters $R_0 = 4.0$ fm and $P_0 = 0.3$ GeV/c are chosen by fitting the proton rapidity distribution at bombarding energy of $\sqrt{s_{NN}} = 2.7$ GeV for central Au+Au collisions. This parameter set gives fairly good description of the rapidity distribution of protons for a wide range of collision energies. Nuclear clusters are generally not in their ground states, but in excited states. Thus the statistical decay of such excited fragments are also taken into account [13]. In the statistical decay model (SDM), we include the emissions of nuclei up to the mass number of 4 as well as gamma emission.

3. Results

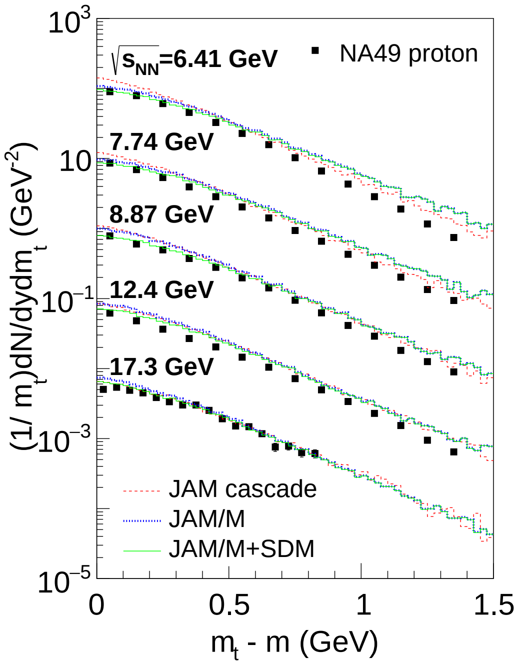

Fig. 1. Transverse mass distributions for protons in central Pb+Pb collisions at $\sqrt{s_{NN}} = 6.41 - 17.3$ GeV [14] is compared to JAM cascade mode (dashed lines), and JAM/M (dotted lines), and JAM/M+SDM (solid lines).

In Fig. 1, we compare the transverse mass distributions of protons in central Pb+Pb collisions at $\sqrt{s_{NN}} = 6.41 - 17.3$ GeV from NA49 [14] with the JAM results. The spectra are scaled down by successive factors of 10 from the 6.41 GeV data. The proton distributions from JAM cascade mode (dashed lines) overestimate the yield at low transverse mass region. It is seen that JAM mean-field calculation (JAM/M) suppresses the yields of the low transverse momentum except the highest NA49 energy, but still predicted yields are slightly higher than the data.

It is found that the proton stopping can be improved by taking into account nuclear cluster formations [15], which contributes to about 20% reduction of the proton rapidity distribution. We also found the similar results which affect the transverse mass distribution in the low transverse mass region. Inclusion of nuclear cluster formation improves the description of the proton transverse mass distribution as shown in the Fig.1 (JAM/M+SDM). In general, nuclear fragments are in the excited states and decay by emitting particles. Thus their statistical decay into the ground state should be considered. It turns out that cluster formation affects the low transverse mass region, but the contribution of the statistical decay is negligibly small in the NA49 energy ranges. We found that the statistical decay of nuclear cluster is only important at lowest AGS energy. The effect of the mean-field at higher transverse mass region is to harden the spectra at lower collision energies of 6.41 and 7.74 GeV.

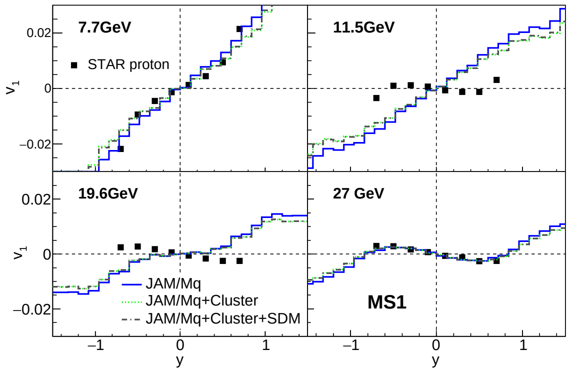

Fig. 2. Directed flows of protons in mid-central Au+Au collisions (10-40%) at $\sqrt{s_{NN}} = 7.7 - 27$ GeV from JAM mean-field mode (dashed lines), and JAM mean-field followed by the statistical decay (solid lines) in comparison with the STAR data [10].

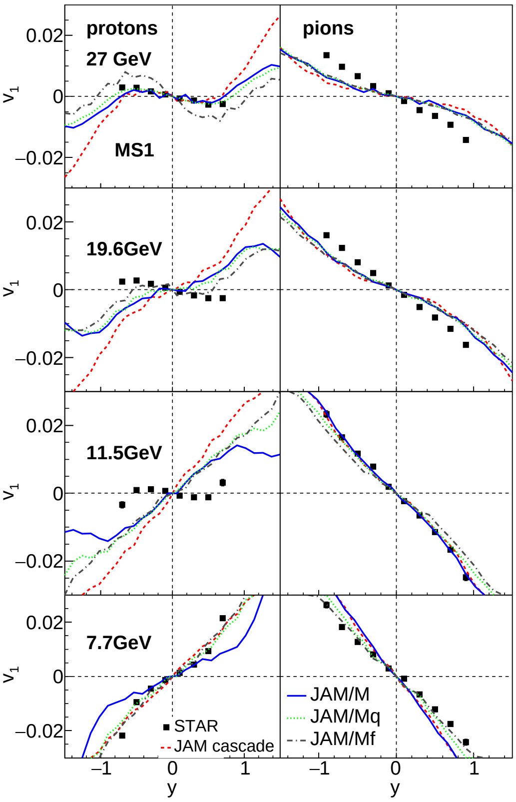

Fig. 3. Directed flows of protons and pions in mid-central Au+Au collisions (10-40%) at $\sqrt{s_{NN}} = 7.7 - 27$ GeV from JAM cascade mode (dashed lines), and JAM cascade with attractive orbit (solid lines) in comparison with the STAR data [10].

Let us now discuss the potential effects and formation of nuclear clusters on the directed flow. First we study the effect of nuclear cluster formation and its decay on the v_1. In Fig. 2, we compare proton directed flow to the STAR data for mid-central Au+Au collisions [10]. It is seen that the effect of nuclear cluster formation on the proton v_1 is about 15%, and the effect of the statistical decay of nuclear cluster is very tiny. Thus we conclude that formation of nuclear cluster and its decay plays no role in the proton v_1 at mid-rapidity from the viewpoint of the softening of the EoS.

Figure 3 shows the rapidity dependence of the proton and pion directed flow for mid-central Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6$ and 27 GeV. JAM cascade agree with the 7.7 GeV data, but JAM cascade predictions does not show negative slopes at both 11.5 and 19.6 GeV, which disagree with the data. The negative slope of v_1 at 27 GeV may be due to a geometrical effect as discussed in Refs. [5, 6].

We tested three different implementations of the baryon potentials. In the JAM/M model, potentials are only included for the formed baryons (solid lines). String excitation dominates the particle productions in the energy ranges considered here, and there are many hadrons which are not formed during a formation time (pre-formed hadrons). However, leading hadrons normally contain original constituent quarks, and they may interact with other hadrons. Interaction of constituent quarks are included effectively in the two-body collision term by reducing the hadronic cross sections [16]. We apply the same idea for the mean field part (JAM/Mq): hadrons which has original constituent (di)quarks interact by reducing the strength of the potential by (2/3) 1/3 during their formation time. The results from the model JAM/Mq are plotted in the dotted lines. Finally, we also display the results of JAM/Mf in which all hadrons including preformed hadrons fully feel potentials, in order to see somewhat maximum effects of the baryon potentials. From the results obtained by three scenarios, it is seen that the effects of hadronic mean-field is large, and to reduce the slope of the proton directed flow, but still incompatible to the data. Namely, our model predict positive dv_1/dy at 11.5 and 19.6GeV.

On the other hand, pion directed flow is not largely affected by the mean-field, since the meson is affected indirectly from baryons, not from meson mean-field in the current model.

4. Conclusion

In conclusion, we have examined the effects of baryon mean-field potentials as well as the nuclear cluster formations and their statistical decays on the directed flow at BES energies by the hadronic transport model JAM. The Skyrme-type density dependent and Lorentzian-type momentum dependent mean field potentials are implemented within a framework of RQMD/S. We found that the baryon mean-field reduces the slope of dv_1/dy by 20-30 %. The effect of nuclear cluster formation on the proton spectra as well as v_1 is also found to be about 10-20%. Contributions from the statistical decay of nuclear fragment is very small. We tested three different implementations of potentials. All of them cannot explain the correct beam energy dependence of the proton directed flow especially at the transition region of the reverse of the dv_1/dy around $9 \lessapprox \sqrt{s_{NN}} \lessapprox 20$ GeV. We finally remark that the negative dv_1/dy at 11.5 and 19.6 GeV can be described by the transport approach if the effects of the softening of the EoS is taken into account [17].

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