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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 become 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.

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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 is 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 is 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 is 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

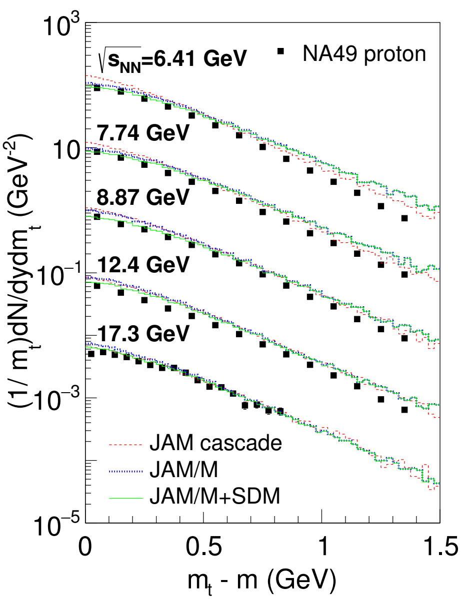

Fig. 1. Transverse mass distributions for protons in central Pb+Pb collisions at $\sqrt{s_{NN}} = 6.41 - 17.3$ GeV [14] are compared to JAM cascade mode (dashed lines), and JAM/M (dotted lines), and JAM/M+SDM (solid lines).

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