Directed flow in heavy-ion collisions and softening of equation of state *

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We analyze the directed flow of protons and pions in high-energy heavy-ion collisions in the incident energy range from $\sqrt{s_{NN}} = 7.7$ to 27 GeV within a microscopic transport model. While standard hadronic transport approaches do not describe the collapse of directed flow below $\sqrt{s_{NN}} \simeq 20$ GeV, a model that simulates effects of a softening of the equation of state by introducing the attractive orbits describes well the behavior of directed flow data. The equation of state with the attractive orbits is as soft as the one with the first-order phase transition.

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1. Introduction

A first-order QCD phase transition (FOPT) may exist at finite baryon densities, and its detection is of primary interest in current nuclear physics. The FOPT is also important for current searches of gravitational wave signatures from binary neutron star mergers [1]. This issue can be studied under controlled circumstances in the laboratory by relativistic heavy-ion collisions, with the help of an appropriate nonequilibrium theory which includes realistic equation of state (EoS) at finite densities. Among various observables, we focus on the directed flow (v_1). The negative flow ($dv_1/dy < 0$) grows if matter passes through the softening point of EoS in a tilted ellipsoid, then the collapse of the directed flow slope to a negative value observed at 10 GeV $< \sqrt{s_{NN}} <$ 20 GeV in the beam energy scan (BES) program at RHIC [2] might signal the softening of EoS, and consequently,

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a FOPT. Actually, the slope is predicted to show a minimum at a certain collision energy in hydrodynamical calculations using an equation of state (EoS) with a FOPT [3]. The negative slope has been predicted also in microscopic transport models, but the origin of the sign change is purely geometrical and only happens at large impact parameters and sufficiently higher collision energies, $\sqrt{s_{NN}} > 20$ GeV [4, 5]. The hadronic transport model with momentum dependent mean field describes the directed flow data in the corresponding energy region [6] better, but does not explain the negative slope of proton v_1 [7]. Thus the collapse of directed flow below $\sqrt{s_{NN}} \leq 20$ GeV gives indirect evidence of the phase transition around such collision energies.

In the present proceedings, we investigate the directed flow in the BES energy region within the microscopic transport model JAM [8] by imposing attractive orbits for each two-body scattering to simulate effects of a softening of the EoS [9].

2. EoS softening effects on directed flow slope

We take into account nuclear EoS effects in the hadronic transport model JAM [8] by changing the stochastic two-body scattering style [10, 11, 12], which is normally implemented so as not to contribute to the pressure. By imposing attractive orbits for each two-body hadron-hadron scattering, the pressure is reduced as given by the virial theorem [12]

$$P = P_f + \frac{1}{3V\Delta t} \sum_{(i,j)} \boldsymbol{q}_{ij} \cdot (\boldsymbol{r}_i - \boldsymbol{r}_j) \tag{1}$$

where $P_f = 1/(3V\Delta t) \int dt \sum_i \boldsymbol{p}_i \cdot \boldsymbol{v}_i$ corresponds to the kinetic contribution. The second term represents the pressure from two-body scatterings, where $\boldsymbol{q}_{ij} = \boldsymbol{p}'_i - \boldsymbol{p}_i = -(\boldsymbol{p}'_j - \boldsymbol{p}_j)$ is the momentum transfer and $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are the coordinates of colliding particles i and j. V is the volume of the system, and Δt is a time interval over which the system is measured. Thus, repulsive orbits $\boldsymbol{q}_{ij} \cdot (\boldsymbol{r}_i - \boldsymbol{r}_j) > 0$ enhance the pressure, while attractive orbits $\boldsymbol{q}_{ij} \cdot (\boldsymbol{r}_i - \boldsymbol{r}_j) < 0$ reduce the pressure. Attractive orbits are implemented in the simulation by exchanging the momentum of two particles in the two-body center-of-mass (c.m.) frame when the randomly chosen scattering orbit is repulsive. While in reality softening of EoS should depend on the local energy density and temperature, we impose a modified scattering style for all hadron-hadron $2 \to 2$ scatterings in order to examine the softening effects.

In the left panel of Fig. 1, we show the calculated directed flow v_1 of protons and pions as functions of rapidity in mid-central collisions from the

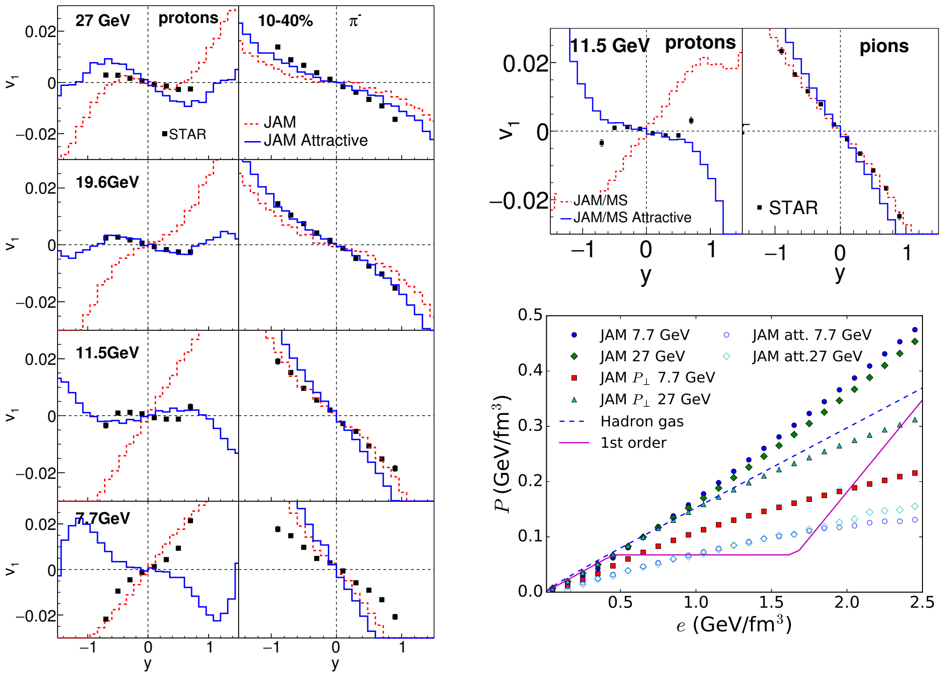

Fig. 1. Left: Directed flows of protons and pions in mid-central Au+Au collisions (10-40%) at $\sqrt{s_{NN}} = 7.7$-27 GeV from the standard cascade (dashed lines) and the cascade with attractive orbits (solid lines) in comparison with the STAR data [2]. Right top: Directed flows calculated with momentum dependent hadronic mean-field potentials (JAM/MS) at $\sqrt{s_{NN}} = 11.5$ GeV. Solid and dashed lines show results of JAM/MS in the standard and attractive orbit modes, respectively. Right bottom: Effective EoS extracted from the time evolution of simulations in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ and 27 GeV. Full (open) circles and diamonds represent the pressures P at from standard JAM (JAM with attractive orbits) at 7.7 and 27 GeV, respectively. The dashed and sold lines represent the EoS from hadron gas and the EoS with a first-order phase transition used in Ref. [15]. Taken from Ref. [9].

standard cascade (dotted lines) and the cascade with attractive orbits (solid line) in Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6$ and 27 GeV [9] in comparison with the STAR data [2]. While the standard cascade results agree with the 7.7 GeV data, v_1 from the standard cascade for beam energies of 11.5 and 19.6 GeV yields much larger v_1 slope than the data. By comparison, attractive orbits drastically reduce the v_1 slope, and explain the STAR data at $\sqrt{s_{NN}} \gtrsim 10$ GeV. Particularly, the v_1 slope becomes almost zero and negative at $\sqrt{s_{NN}} = 11.5$ and 19.6 GeV, respectively. At lower energy

$\sqrt{s_{NN}} = 7.7$ GeV, results with attractive orbits are far from the data.

The proton v_1 slope at $\sqrt{s_{NN}} = 27$ GeV and pion v_1 slopes are negative in the standard cascade from geometrical non-QGP effects [4] and from absorption by baryons [13], respectively, and there is no sign change in the v_1 slope by the EoS softening effects. It should be noted, however, that JAM with attractive orbits overestimates the negative slope of the proton v_1 indicating the need of EoS rehardening, i.e. created matter at this collision energy reaches well above the transition region or less net baryonic density leads to weaker softening of the EoS.

Next we examine the nuclear mean field effects. Skyrme-type density dependent and Lorentzian-type momentum dependent nuclear mean field of baryons are included based on the framework of simplified version of relativistic quantum molecular dynamics (RQMD/S) in Ref. [7], but with slightly different parameter sets which yields the incompressibility of $K = 272$ MeV [14]. The mean field slightly reduces the proton directed flow, but the basic trend is the same as the cascade as shown in the right top panel of Fig. 1 [9]. We note that attractive orbits supplemented by the mean field yields negative slope of proton v_1 at $\sqrt{s_{NN}} = 11.5$ GeV.

The EoS softening by attractive orbits is quantified by the pressure generated by a two-body collision obtained by using the formula [11],

$$\Delta P = -\frac{\rho}{3(\delta\tau_i + \delta\tau_j)} q_{ij}^{\mu}(x_i - x_j)_{\mu} \ , \tag{2}$$

where x_i is the space-time coordinate of particle i, q_{ij} is the four-momentum transfer, ρ is the Lorentz invariant local particle density, and $\delta\tau_i$ is the proper time interval between successive collisions. In the right bottom panel of Fig. 1, we show the "effective EoS" obtained by using the local pressure $P = P_f + \Delta P$ and energy density e at each collision point in the central region [9] in comparison with the ideal hadron gas EoS and the EoS with a FOPT (EOS-Q) [15]. With attractive orbits, we see a significant reduction of the pressure, which is comparable to EOS-Q in the transition region.

3. Summary and discussion

We have investigated the effect of the softening of the EoS on the directed flow of protons and pions in a microscopic transport approach [9]. While the transport model JAM with standard stochastic two-body scattering style fails to explain the negative slope of v_1 below $\sqrt{s_{NN}} \simeq 20$ GeV, the JAM cascade with EoS softening effects implemented by attractive orbit scatterings well describe the STAR data around the minimum of dv_1/dy at $10 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV. The softening effects were not needed at lower ($\sqrt{s_{NN}} = 7.7$ GeV) and higher ($\sqrt{s_{NN}} = 27$ GeV) energies. The deduced

EoS with attractive orbit scatterings is found to show similar pressures as that in the EoS with with a first-order phase transition (EOS-Q) [15]. These observations suggest that the EoS softening is necessary to explain v_1 in heavy-ion collisions at $10 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV.

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