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Excitation function of nucleon and pion elliptic flow in relativistic heavy-ion collisions

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Within a relativistic transport model for heavy-ion collisions, we show that the recently observed characteristic change from out-of-plane to in-plane elliptic flow of protons in midcentral Au+Au collisions as the incident energy increases is consistent with the calculated results using a stiff nuclear equation of state ($K = 380$ MeV). We have also studied the elliptical flow of pions and the transverse momentum dependence of both the nucleon and pion elliptic flow in order to gain further insight about collision dynamics.
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The elliptic flow of hadrons in relativistic heavy-ion collisions has been a subject of great interest as it may reveal the signatures of possible quark-gluon plasma (QGP) phase transitions in these collisions (see Ref. [1] for a recent review). Based on kinematical and geometrical considerations of relativistic heavy-ion collisions, Ollitrault [2] predicted that as the incident energy increases nucleons would change from an out-of-plane elliptical flow to an in-plane one. Such a transition has recently been observed in collisions of heavy ions from the alternating gradient synchrotron (AGS) at the Brookhaven National Laboratory [3–5]. Data from the EOS, E895, and E877 collaborations on the proton elliptic flow in midcentral Au+Au collisions show that the beam energy (E_{tr}) at which the elliptical flow changes sign is about 4 GeV/nucleon [4,5]. Studies based on transport models have indicated that the value for E_{tr} depends on the nuclear equation of state (EOS) at high densities [6,7]. Using a relativistic Boltzmann-equation model (BEM), it has been found that the experimental data can be understood if the nuclear equation of state used in the model is stiff ($K = 380$ MeV) for beam energies below E_{tr} but soft ($K = 210$ MeV) for beam energies above E_{tr} [5]. Since the baryon density reached in heavy-ion collisions at these energies increases with the beam energy, the above study thus suggests that the nuclear equation of state is softened at high densities. Such a softened equation of state may imply the onset of a phase change as suggested by lattice studies of QCD at finite temperature and zero baryon chemical potential. However, to put this conclusion on a firm ground requires further studies using other models. In this Rapid Communication, we shall study the elliptical flow in heavy-ion collisions at AGS energies using a relativistic transport (ART) model [8] and show that the experimental data are consistent instead with the prediction using a stiff EOS without invoking a softening at high densities [9]. Furthermore, we shall show that by studying both the nucleon and pion elliptic flow as a function of beam energy and transverse momentum one can obtain much more information about the reaction dynamics and the origin of the transition in the sign of elliptic flow.

Our study is based on the relativistic transport model ART for heavy-ion collisions. We refer the reader to Ref. [8] for details of the model and its applications in studying various aspects of relativistic heavy-ion collisions from Bevalac to AGS energies. The elliptic flow reflects the anisotropy in the particle transverse momentum (p_t) distribution at midrapidity, i.e., $v_2 \equiv \langle (p_x^2 - p_y^2)/p_t^2 \rangle$, where the average is taken over all particles of a given kind in all events [10]. In the upper panel of Fig. 1, we compare the excitation function of v_2 for protons in midcentral Au+Au reactions obtained using the stiff (cross), soft (filled square) EOS, and the cascade

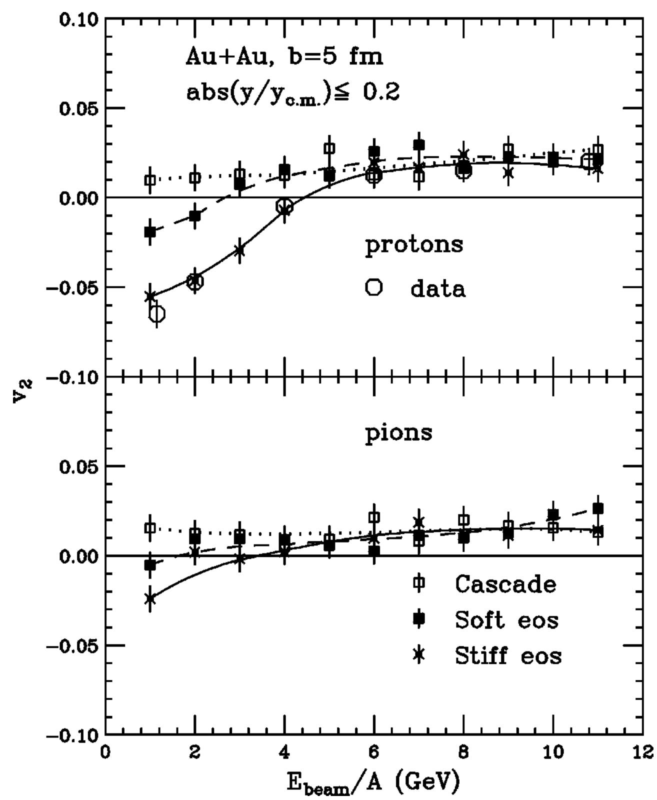

FIG. 1. The excitation function of proton (upper) and pion (lower) elliptic flow in midcentral Au+Au reactions.

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(open square) with the experimental data (open circles) of Ref. [5]. An impact parameter of 5 fm, which is consistent with that in the data analysis [5,11], is used in the calculations. In agreement with other model calculations [6,7,12], our calculated results also show that the transition energy in the proton elliptic flow is very sensitive to the nuclear EOS. The value of E_{tr} is more than 4 GeV/nucleon in the case of a stiff EOS but decreases to below 3 GeV/nucleon for a soft EOS. As discussed in Ref. [7], a soft EOS, which gives a smaller sound velocity than that of a stiff EOS, reduces the squeeze-out contribution and thus leads to a smaller transition energy in proton elliptic flow. In the case of cascade calculations, the absence of a repulsive potential further reduces the squeeze-out contribution and results in an essentially in-plane flow in the beam energy range considered here. On the other hand, the value of v_2 in our calculations is insensitive to the nuclear EOS for incident energies above about 6 GeV/nucleon. This is different from the results of Ref. [7], where a distinct difference is seen between the elliptic flow due to a soft and a stiff EOS. Our results also differ from that of Ref. [12] based on the ultrarelativistic quantum molecular dynamics (UrQMD), in which the elliptical flow in the case of a stiff EOS is much smaller than that from the cascade model even for incident energies above 6 GeV/nucleon. However, in both our study and that from the UrQMD the experimental data are found to be consistent with the calculated results using the stiff EOS in this beam energy range. These results are thus different from that of Ref. [5], where calculations based on the BEM show that the experimental data suggest a softening of the EOS from a stiff one at low beam energies to a softer one at higher energies. Since different model calculations lead to different dependence of the proton elliptical flow on the nuclear EOS, it is thus not possible at present to draw conclusions from comparisons of the theoretical results with the experimental data. To test these theoretical models, simultaneous studies of other experimental observables will be useful.

Since pions are abundantly produced in high energy heavy-ion collisions, their elliptical flow is expected to provide further insight about collision dynamics. In the lower panel of Fig. 1, we show our predictions for the excitation function of the pion elliptic flow. All three charge states of the pion are included in the analysis. Effects due to the different charges will be discussed in the next paragraph. It is shown that pions also show a transition from out-of-plane to in-plane elliptic flow as the beam energy increases. However, both the magnitude of pion elliptic flow and the transition energy at which it changes sign are significantly smaller than those for nucleons. This can be qualitatively understood from the collision dynamics. For nucleons, the sign and magnitude of elliptic flow depends on both transverse expansion time of participant nuclear matter and the passage time of the two colliding nuclei. The latter reflects the time scale for the spectators to be effective in preventing the participant hadrons from developing an in-plane flow, thus enhancing the squeeze-out contribution to the elliptical flow. For pions, however, the shadowing effect due to spectator nucleons is less important as a result of the time delay in their production, i.e., a significant number of pions are emitted later in the reaction from the decay of both baryon and meson resonances after the spectator nucleons have already moved away. Therefore, both the magnitude of squeeze-out contribution and the transition energy in the pion elliptic flow are significantly smaller than those of nucleons. The study of the excitation function of both nucleon and pion flow is useful in understanding the origin of the transition from out-of-plane to in-plane elliptic flow.

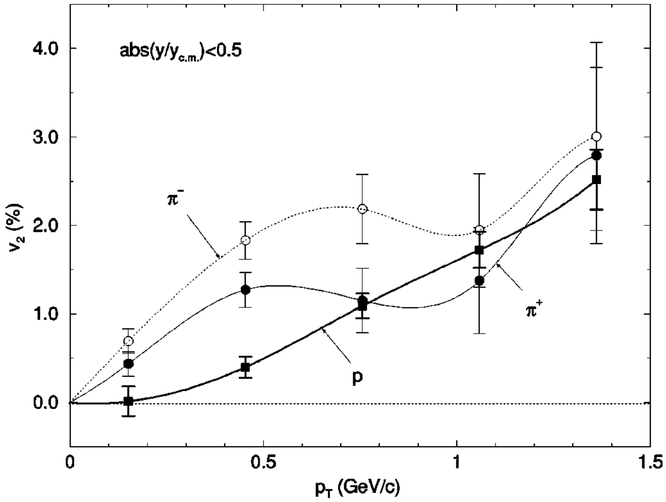

FIG. 2. The transverse momentum dependence of nucleon and pion elliptic flow in the reaction of Au+Au at $p_{\mathrm{beam}}/A = 6$ GeV/c and an impact parameter of 4 fm using a soft nuclear equation of state.

In Fig. 2, we show the p_t dependence of nucleon and pion elliptic flow in a midcentral collision of Au+Au at a beam momentum of 6 GeV/c. They are obtained from the ART model with a soft nuclear EOS. For protons, the elliptic flow increases approximately quardratically at low p_t and then increases linearly at high p_t, as expected from the nucleon azimuthal angle distributions [1,13,14]. For pions, their v_2 value is larger than that for protons at low p_t but becomes similar at high p_t. Again, one can understand this result from the reaction dynamics. Low p_t pions are more likely produced later in the reaction, and they are thus less likely to be shadowed by spectator nucleons and have thus a larger in-plane flow compared to low p_t protons. On the other hand, high p_t pions are mainly produced early in the reaction and thus freeze out together with high p_t nucleons, leading then to a similar elliptic flow, which approaches that of the hydrodynamical limit [14]. It is interesting to mention that the observed p_t dependence of v_2 for nucleons and pions is remarkably similar to that found at both Bevalac/SIS [13,15] and SPS energies [16], indicating the similarity of the collision dynamics at these different energies. We note that negative pions have higher in-plane flow than the positive ones as a result of the Coulomb potential from protons, i.e., negative pions are attracted to while positive ones are repelled away from the reaction plane by protons.

In summary, using a relativistic transport model we have found that the transition from out-of-plane to in-plane elliptic flow in midcentral Au+Au collisions as the beam energy increases is consistent with a stiff nuclear EOS without invoking a phase transition. This result is consistent with that from the UrQMD model but different from that from the BEM. To help disentangle these different predictions, we have also shown the excitation function of the pion elliptic flow and the transverse momentum dependence of both the nucleon and pion elliptic flow, which are expected to reveal interesting information about both the reaction dynamics and the origin of the observed change in the sign of elliptic flow.

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