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A Dynamical Quark Coalescence Approach to ϕ and Ω Anisotropic Flows and Their Scaling in Heavy-Ion Collisions at RHIC*

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Abstract We report the results on anisotropic flows and their scaling for ϕ mesons and Ω ($\Omega^-+\bar{\Omega}^+$) baryons in Au+Au collisions at RHIC, obtained from a dynamical quark coalescence model that uses the quark phase-space information from a multi-phase transport (AMPT) model within the string melting scenario and includes the quark structure of hadrons.

Key words anisotropic flows, flow scaling, quark coalescence model

1 Introduction

Recently, there is a lot of interest in using the quark coalescence or recombination model to understand the experimental data from heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC). As shown in Refs. [1—4], the quark coalescence model can explain successfully the observed anomalously large enhancement of baryon to meson ratio at intermediate transverse momenta and scaling of the elliptic flow of identified hadrons according to their valence quark numbers. Most of these studies were based on a simple momentum-space coalescence in which only quarks with same momentum can coalesce into hadrons. Also, the phase-space information of quarks in the partonic matter produced in relativistic heavy-ion collisions was usually taken from a schematic fireball model. We have, however, recently used a dynamical quark coalescence model, that is based on the quark phase-space information from a multi-phase transport (AMPT) model within the string melting scenario and takes into consideration the hadron quark wave functions, to study the production and anisotropic flow of ϕ mesons and Ω ($\Omega^- + \bar{\Omega}^+$) baryons that consist of strange quarks in Au+Au collisions at RHIC[5].

2 Anisotropic flows of strange and antistrange quarks

The AMPT model in the string melting scenario[6] has been shown to describe successfully both the elliptic flow[7] and pion interferometry[8] measured at RHIC. For Au+Au collisions at $\sqrt{s_{\rm NN}}=200$GeV and b = 8fm, the $p_{\rm T}$ dependence of the parton elliptic flow v_2 and forth-order anisotropic flow v_4 is shown in Fig. 1. It is seen that strange and antistrange quarks exhibit not only a strong v_2 (solid squares) but also a non-negligible v_4 (open squares) that approximately scales with v_2^2 with a scaling coefficient of 0.85, i.e, $v_4 \sim 0.85 v_2^2$, as shown by the thick solid line. Compared to the v_2 of mid-rapidity light up

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and anti-up quarks $(\mathrm{u}+\bar{\mathrm{u}})$, shown by triangles, v_2 of heavier strange and antistrange quarks has a smaller value at low p_T but a larger value at high p_T, similar to the mass ordering of hadron elliptic flows in the hydrodynamic model. However, instead of a continuing increase of v_2 with respect to p_T as seen in the hydrodynamic model, v_2 of partons in the transport model saturates at a maximum value when their p_T becomes large, indicating that high momentum partons do not reach thermal equilibrium with the bulk of the partonic matter.

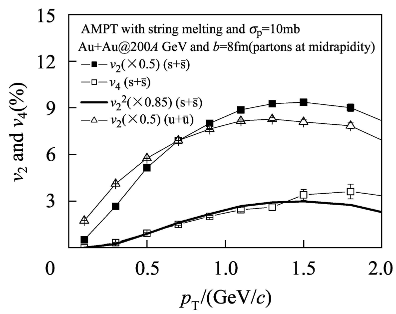

Fig. 1. (Color online) Transverse momentum dependence of v_2 and v_4 for mid-rapidity partons.

3 ϕ and Ω anisotropic flows and their scaling

In the coalescence model, the probability of forming a bound cluster from a many-particle system is determined by the overlap of the wave functions of coalescing particles with the internal wave function of the cluster[9, 10]. Using above strange and antistrange quarks phase-space information from the AMPT model and taking the hadron quark wave functions to be that of a spherical harmonic oscillator with their radius parameters fixed from fitting measured yields of ϕ mesons and Ω baryons[5], the transverse momentum spectra of ϕ mesons and Ω baryons as well as their anisotropic flows in relativistic heavy-ion collisions can then be calculated. In particular, from fitting measured yields of ϕ mesons and Ω baryons at mid-rapidity in central Au+Au collisions at $\sqrt{s_\mathrm{NN}}=200\mathrm{GeV}$, we find the resulting hadron radii are $R_\phi = 0.65\mathrm{fm}$ (fitting the STAR data) or 0.47fm (fitting the PHENIX data) and $R_\Omega = 1.2\mathrm{fm}$.

Shown in Fig. 2 is the p_T dependence of the anisotropic flows v_2 and v_4 of mid-rapidity ϕ mesons and Ω baryons produced in Au+Au collisions at $\sqrt{s_\mathrm{NN}}=200\mathrm{GeV}$ and $b=8\mathrm{fm}$. Solid and open squares are, respectively, the ϕ meson v_2 and v_4 for a ϕ meson radius $R_\phi = 0.65\mathrm{fm}$, while solid and open triangles are, respectively, those for $R_\phi = 0.47\mathrm{fm}$. It is seen that the scaling relation $v_4(p_\mathrm{T}) \sim v_2^2(p_\mathrm{T})$ is satisfied in both cases as shown by the solid $(1.1v_2^2)$ and dashed $(1.2v_2^2)$ lines in the same figure, and the scaling coefficient of 1.1 or 1.2 is similar to that extracted from the data for charged hadrons[11, 12]. Similar results for Ω baryons using the radius $R_\Omega = 1.2\mathrm{fm}$ are shown in the right panel of Fig. 2. The scaling relation $v_4(p_\mathrm{T}) \sim v_2^2(p_\mathrm{T})$ is again satisfied for Ω baryons but with a smaller scaling coefficient than that for ϕ mesons as shown by the solid line $(0.7v_2^2)$ in the right panel.

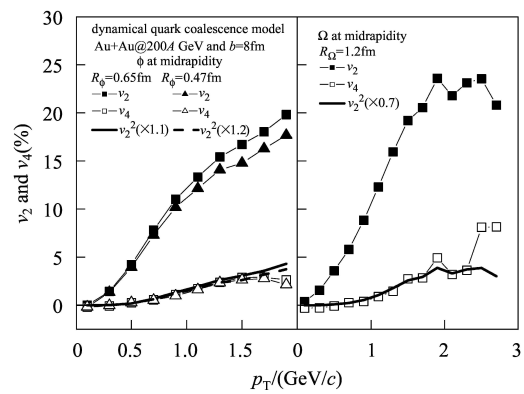

Fig. 2. (Color online) Transverse momentum dependence of v_2 and v_4 of mid-rapidity ϕ mesons (left panel) and Ω baryons (right panel).

Based on the naive momentum-space quark coalescence model that only allows quarks with equal momentum to form hadrons[4], the scaling relation between hadron $v_2(p_\mathrm{T})$ and $v_4(p_\mathrm{t})$ has been attributed to a similar scaling relation between those of quarks[13, 14]. Neglecting the small contribution of higher-order anisotropic flows (higher than forth-order), this model gives for mid-rapidity hadrons

$$\begin{aligned} \frac{v_{4,\mathrm{M}}(2p_\mathrm{T})}{v_{2,\mathrm{M}}^2(2p_\mathrm{T})} &\approx \frac{1}{4}+\frac{1}{2}\frac{v_{4,\mathrm{q}}(p_\mathrm{T})}{v_{2,\mathrm{q}}^2(p_\mathrm{T})}, \\ \frac{v_{4,\mathrm{B}}(3p_\mathrm{T})}{v_{2,\mathrm{B}}^2(3p_\mathrm{T})} &\approx \frac{1}{3}\left(1+\frac{v_{4,\mathrm{q}}(p_\mathrm{T})}{v_{2,\mathrm{q}}^2(p_\mathrm{T})}\right), \end{aligned} \tag{1}$$

where $v_{\mathrm{n,M}}(p_\mathrm{T})$, $v_{\mathrm{n,B}}(p_\mathrm{T})$ and $v_{\mathrm{n,q}}(p_\mathrm{T})$ denote, respectively, the meson, baryon, and quark anisotropic flows. Hadron anisotropic flows thus satisfy the scaling relation $v_4(p_T) \sim v_2^2(p_T)$ if a similar scaling relation is satisfied by quark anisotropic flows. With the scaling relation $v_{4,q}(p_T)/v_{2,q}^2(p_T) \approx 0.85$ for mid-rapidity strange and antistrange quarks as shown in Fig. 1, Eq. (1) then leads to a scaling coefficient of $v_{4,\phi}(p_T)/v_{2,\phi}^2(p_T) \approx 0.68$ for ϕ mesons and $v_{4,\Omega}(p_T)/v_{2,\Omega}^2(p_T) \approx 0.62$ for Ω baryons. The predicted scaling coefficient for ϕ mesons is significantly smaller than its value 1.1 or 1.2 from the dynamical quark coalescence model. The latter does give, however, a larger scaling coefficient for ϕ mesons than for Ω baryons as in the naive momentum-space coalescence model.

Another interesting and important finding in heavy-ion collisions at RHIC is the valence quark number scaling of the elliptic flow of identified hadrons, i.e., the elliptic flow per valence quark in a hadron is same at same transverse momentum per valence quark, i.e., $v_{2,H}(p_T/n_q)/n_q = v_{2,q}(p_T)$ with $v_{2,H}$ and n_q denoting, respectively, the hadron v_2 and the number of valence quarks or anti-quarks in a hadron. In the naive momentum-space quark coalescence model, this scaling can be shown to be satisfied if high-order anisotropic flows are small[4, 14]. The scaling is, however, broken in more general quark coalescence models that take into account the quark momentum distribution[15—17] and higher parton Fock states[18] in hadrons as well as the effect of resonance decays[15]. For ϕ meson and Ω baryon v_2 obtained from our dynamical quark coalescence model, their valence quark number scaled elliptic flows as functions of scaled transverse momentum are shown in the right panel of Fig. 3. For comparison, we also include the elliptic flow of mid-rapidity strange and antistrange quarks at freeze-out. It is seen that the elliptic flows of ϕ mesons and Ω baryons satisfy the valence quark number scaling. However, their valence quark number scaled elliptic flows are significantly smaller than that of coalescing strange and antistrange quarks. Our results therefore indicate that cautions are needed in interpreting the elliptic flow of partons from that of hadrons using the naive momentum-space parton coalescence model.

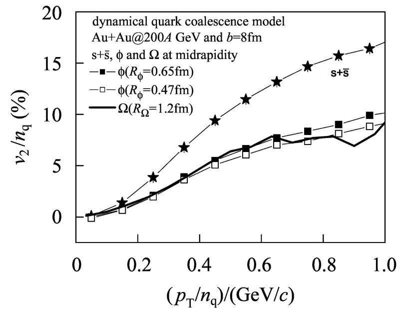

Fig. 3. (Color online) Valence quark number scaled elliptic flow as a function of scaled transverse momentum for mid-rapidity ϕ mesons and Ω baryons.

In above calculations, we have used ϕ meson and Ω baryon size parameters that are fixed from fitting measured yields in experiments. Using different size parameters affects the v_2 and v_4 of ϕ mesons and Ω baryons, and it is found that the later increase with increasing size parameter and saturates when hadron radii are greater than about 4.5fm, as shown in Fig. 4. The saturation of ϕ meson and Ω baryon v_2 at large sizes is essentially due to the fact that the dynamical quark coalescence model approaches the naive momentum-space quark coalescence model when the hadron size is sufficiently large.

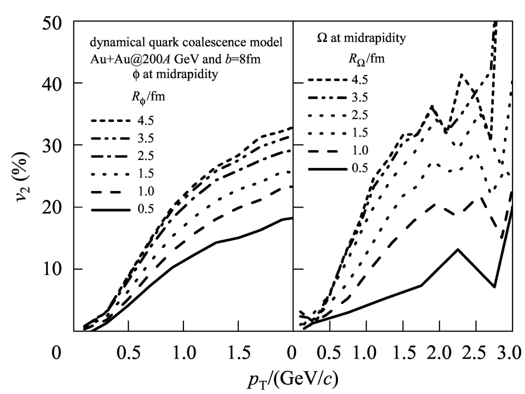

Fig. 4. (Color online) Transverse momentum dependence of the v_2 for mid-rapidity ϕ mesons (left panel) and Ω baryons (right panel) in Au+Au collisions at $\sqrt{s_{NN}} =$ 200GeV and $b = 8$fm with different values of root-mean-square radii R_ϕ and R_Ω.

4 Conclusions

Based on the parton phase-space information obtained from a multi-phase transport model within the string melting scenario, we have studied the anisotropic flows of ϕ mesons and Ω baryons in Au+Au collisions at RHIC using a dynamical quark coalescence model, which requires information on the radii of ϕ meson and Ω baryon. Fixing their radii by fitting measured yields of ϕ mesons and Ω baryons at mid-rapidity in central Au+Au collisions at $\sqrt{s_{\rm NN}}=$ 200GeV, we have evaluated their anisotropic flows in the same collision at impact parameter $b=8$fm. We have found that the elliptic flows of ϕ mesons and Ω baryons follow approximately the valence quark number scaling. The valence quark number scaled elliptic flows of ϕ mesons and Ω baryons deviate, however, significantly from the underlying v_2 of strange and antistrange quarks. We have also studied the forth-order anisotropic flow v_4 and found that the scaling relation of $v_4(p_{\rm T})\sim v_2^2(p_{\rm T})$ observed experimentally for charged hadrons is also satisfied by ϕ mesons and Ω baryons. In addition, the anisotropic flows have been shown to increase with increasing hadron size and saturates when hadron radii are large enough and the dynamical quark coalescence model approaches the naive momentum-space quark coalescence model.

References

1 Greco V, Ko C M, Lévai P. Phys. Rev. Lett., 2003, **90**: 202302; Phys. Rev., 2003, **C68**: 034904

2 Hwa R C, Yang C B. Phys. Rev., 2003, **C67**: 034902; idib., 2003, **67**: 064902

3 Fries R J, Müller B, Nonaka C et al. Phys. Rev. Lett., 2003, **90**: 202303; Phys. Rev., 2003, **C68**: 044902

4 Molnar D, Voloshin S A. Phys. Rev. Lett., 2003, **91**: 092301

5 CHEN L W, Ko C M. Phys. Rev., 2006, **C73**: 044903

6 LIN Z W, Ko C M, LI B A et al. Phys. Rev., 2005, **C72**: 064901

7 LIN Z W, Ko C M. Phys. Rev., 2002, **C65**: 034904

8 LIN Z W, Ko C M, Pal S. Phys. Rev. Lett., 2002, **89**: 152301

9 Mattiello R, Jahns A, Sorge H et al. Phys. Rev. Lett., 1995, **74**: 2180; Mattiello R, Sorge H, Stocker H et al. Phys. Rev., 1997, **C55**: 1443

10 CHEN L W, Ko C M, LI B A. Phys. Rev., 2003, **C68**: 017601; Nucl. Phys., 2003, **A729**: 809

11 Adams J et al. (STAR Collaboration). Phys. Rev. Lett., 2004, **92**: 062301

12 Adams J et al. (STAR Collaboration). Phys. Rev., 2005, **C72**: 014904

13 CHEN L W, Ko C M, LIN Z W. Phys. Rev., 2004, **C69**: 031901(R)

14 Kolb P F, CHEN L W, Greco V et al. Phys. Rev., 2004, **C69**: 051901(R)

15 Greco V, Ko C M. Phys. Rev., 2004, **C70**: 024901

16 Greco V, Ko C M. arXiv:nucl-th/0505061

17 Pratt S, Pal S. Phys. Rev., 2005, **C71**: 014905; Nucl. Phys., 2005, **A749**: 268c

18 Muller B, Fries R J, Bass S A. Phys. Lett., 2005, **B618**: 77