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Difference in Elliptic Flow Between Particles and Antiparticles in Au+Au Collisions at $\sqrt{s_{\rm NN}}=7.7\sim62.4$ GeV in UrQMD

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Abstract: The elliptic flow for proton, π^+, K^+ and their corresponding antiparticles are investigated at mid-rapidity for Au+Au collisions at $\sqrt{s_{\rm NN}}=7.7$, 11.5, 19.6, 27, 39, 62.4 GeV, utilizing ultrarelativistic quantum molecular dynamics (UrQMD-3.3p1). We analyze the difference in $v_2(p_{\rm T})$ between the particles and the corresponding antiparticles as a function of the transverse momentum $p_{\rm T}$. We find that in UrQMD the v_2 for K^- is larger than that for K^+ at all BES energies. The $v_2(p_{\rm T})$ values are almost identical for π^+ and π^- at $7.7\sim62.4$ GeV. While in experiments, at lower energies, 7.7, 11.5 and 19.6 GeV, $v_2(\pi^-)$ is larger than $v_2(\pi^+)$ for all $p_{\rm T}$ values. We can clearly see that in UrQMD the v_2 for antiproton is larger than that for proton at all BES energies, which is in contradiction to the experimental result. The opposite trend observed in experiment is therefore an indication that the strong coupling in heavy ion collision and the non equilibrium in transport process may need further understanding.

Key words: elliptic flow; heavy ion collision; UrQMD

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1 Introduction

Anisotropies in transverse-momentum distributions provide an unambiguous signature of transverse collective flow in ultrarelativistic nucleus-nucleus collisions. A measure of the anisotropy from experimental observables was defined and elliptic flow in ultrarelativistic nuclear collisions was first discussed in Ref. [1]. Fourier analysis of the azimuthal distribution was proposed to study transverse flow effects in relativistic nuclear collisions[2], in which a clear physical meaning to the whole analysis was given. Directed flow v_1 for ultrarelativistic Au+Au collisions, as well as higher harmonics v_2 and v_4 in the event shape were detected for the first time in 1994[3].

Elliptic flow v_2 is more emphasized than v_1 as a signature of QGP formation. The primary reason is that the expansions of the system and subsequent decrease of the spatial anisotropy lead to a self-quenching process for v_2, thereby making it a sensitive probe of the early stage of heavy-ion collisions[4]. In contrast, v_1 has been shown to be mainly sensitive to late time "pion wind" radial pressure gradients[5], which continue to blow long after the QGP condenses into hadronic resonances. Therefore the elliptic flow v_2 is more sensitive to the early evolution of heavy-ion collisions.

2 The Elliptic Flow

In noncentral nuclear collisions, the overlap area has an elliptical almond-like shape. The initial spatial asymmetries decrease rapidly with time as system expanding, when subsequent multi-scattering between particles transform spatial anisotropy into momentum anisotropy. The anisotropy flow is usually defined as the nth Fourier coefficients v_n[2] of the particle distribution, which can be written as[6]

$$\frac{{\rm d}N}{{\rm d}\phi}\propto 1+2\sum_{n=1}^{\infty}v_n\cos[n(\phi-\psi)]\ , \qquad (1)$$

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where ϕ is the particle emission angle and ψ is the event plane angle of the heavy ion collision which is the direction of the short axis of the oval region of the participants. The nth Fourier coefficients v_n can be evaluated by

$$v_n = \langle \cos[n(\phi - \psi)] \rangle \ , \tag{2}$$

the $\langle \cdots \rangle$ denotes mean value for all particles in all events. The second Fourier coefficient v_2 is called elliptic flow, and it is usually characterized in terms of particle momenta by[7]

$$v_2 = \langle \cos[2(\phi - \psi)] \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle . \tag{3}$$

Several interesting observations related to v_2 have been reported in the past decade.

At low transverse momentum ($p_\mathrm{T} < 2$ GeV/c), a mass ordering with heavier particles having smaller v_2 at a given p_T was observed[8–9]. This mass dependence could be explained that elliptic flow is generated by the combination of an azimuthal velocity variation and a spatially anisotropic freeze-out hypersurface. The mass dependence of $v_2(p_\mathrm{T})$ also suggested that in Au+Au collisions at $\sqrt{s_\mathrm{NN}} = 130$ GeV, for central and midperipheral collisions, a system is created which is consistent with early local thermal equilibrium followed by hydrodynamic expansion[8]. At intermediate p_T values ($2 < p_\mathrm{T} < 6$ GeV/c), a number-of-constituent quark (NCQ) scaling of v_2 for the identified hadrons was predicted[10] and then was observed[6] soon afterwards at $\sqrt{s_\mathrm{NN}} = 200$ GeV. This observation, coupled with the comparable values of the elliptic flow measured for multistrange hadrons[11] and light quark hadrons[6], provides convincing evidence that partonic matter may have been created in ultra-relativistic nucleus-nucleus collisions. The created matter was speculated to be strongly interacting quark-gluon plasma(sQGP)[12]. The Beam Energy Scan(BES) program, involving Au+Au collisions at energies of $\sqrt{s_\mathrm{NN}} = 7.7$, 11.5, 19.6, 27, 39 and 62.4 GeV, was proposed at relativistic heavy-ion collider(RHIC) in 2010 to study the properties of the sQGP and its phase transition to hadrons, and to search for critical point. Several interesting phenomena have been observed, in which one of the most striking observations is that the v_2 splitting of particles and the corresponding antiparticles was observed at all transverse momenta at $\sqrt{s_\mathrm{NN}} = 7.7 \sim 62.4$ GeV[13]. The splitting is increasing with decreasing beam energy and is larger for baryons compared to mesons[14]. This result implies that, at lower energies, particles and the corresponding antiparticles are not consistent with the universal NCQ scaling of v_2 that was observed at $\sqrt{s_\mathrm{NN}} = 200$ GeV. If the NCQ scaling of v_2 is an indicator of a QGP phase[15], whether is the breakdown in elliptic flow NCQ scaling observed at the RHIC energy scan related to the turning off of deconfinement? The v_2 splitting between particle and the corresponding antiparticle attracts wide attentions soon. It has been proposed that chiral magnetic wave at finite baryon density in QGP can lead to a charge asymmetry of the elliptic flow in the final momentum space of pions via the collective expansion[16]. But as $\sqrt{s_\mathrm{NN}}$ is reduced, the net baryon number at midrapidity will increase. This phenomenon can also result in violations of simple NCQ scaling[17]. Intriguingly, purely hadronic dynamics has a similar dependence of baryon-antibaryons elliptic flow as purely partonic dynamics, because antibaryons tend to come from regions where the deviation of the system from hydrodynamic behavior is at its smallest[18]. And besides the final state interactions, the initial state, baryon stopping, and baryon number transport for the dynamical evolution of a strongly interacting system produced in heavy ion collisions is also important[19–20]. Both the partonic and hadronic mean-field potentials have effects on the elliptic flow of particles relative to that of their antiparticles[21]. So many factors could influence the v_2 splitting of particles and the corresponding antiparticles. Since it is hadron that is in the beam before heavy ion collision happens, and at the end the particles what we probe are hadrons, leptons and photons, it would be important to study how much the hadronic stage contributes to these observations.

The ultrarelativistic quantum molecular dynamics (UrQMD) transport model[22] is a microscopic many-body approach and is based on the covariant propagation of color strings, constituent quarks, and di-quarks accompanied by mesonic and baryonic degrees of freedom. The constituents are mainly hadrons, for which the ingredients (strings and di-quarks) do not interact with others during their formation time and it does not include quarks and gluons as effective degrees of freedom. The UrQMD model has been applied successfully to explore heavy ion reactions in describing the yields and the p_T spectra of different particles in proton-proton, proton-nucleus, and nucleus-nucleus collisions from AGS energies to the top RHIC energy[23]. Potentials for "preformed" particles (string fragments) from color fluxtube fragmentation as well as for confined particles were found to have influences on the nuclear stopping, the elliptic flow, and the Hanbury - Brown - Twiss (HBT) interferometry[24]. The transverse mass and longitudinal rapidity distributions of experimental data of both

Λs and $\bar{\Lambda}$s can be quantitatively explained fairly well in UrQMD with the consideration of both formed and pre-formed hadron potentials. Both the production mechanism and the rescattering process of hadrons have the equal importance for the final yield of strange baryons[25].

In the present paper, we analysis the elliptic flow of p, $\bar{p}$, K^+, K^-, π^+ and π^- for minimum bias events, in mid-rapidity region, at BES energies, utilizing a hadronic-string transport model— UrQMD-3.3p1. We choose version 3.3p1, not the latest one just because version 3.3p1 does not include quarks and gluons as effective degrees of freedom.

3 Results and Discussions

In present model calculations, the reaction plane angle ψ is taken zero. The calculated and corresponding experimental v_2 values as a function of transverse momentum p_T for identified hadrons for minimum bias (impact parameter $b = 0 \sim 13.42$ fm) events at BES energies are shown in Fig. 1. We can find some similar results in Fig. 4 of Ref. [18]. It is obvious that the UrQMD model generally underestimates the $v_2(p_T)$ values, which was also shown in Fig. 4 of Ref. [24]. It maybe partly because that the UrQMD model does not consider the partonic degrees of freedom which

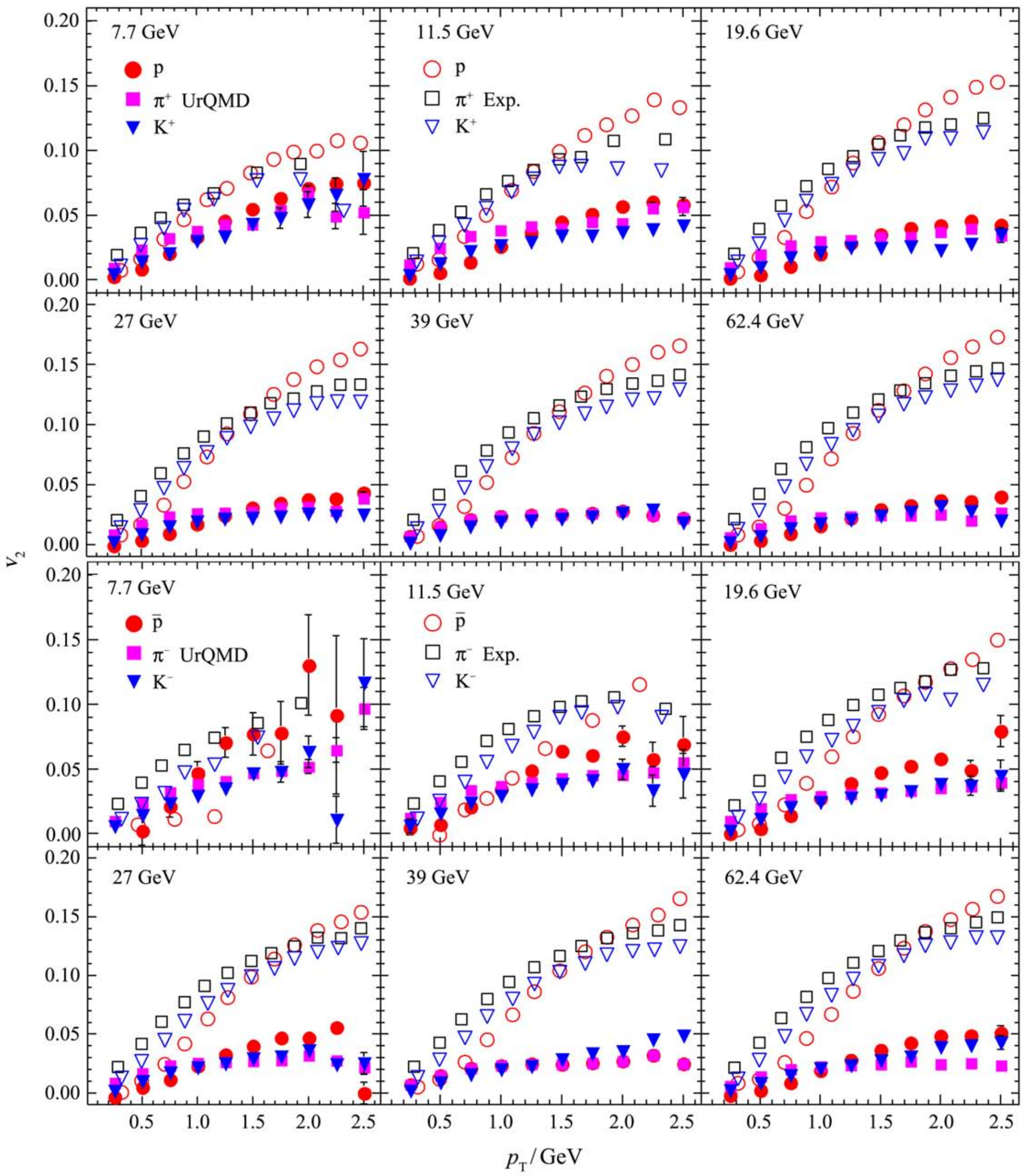

Fig. 1 Transverse momentum dependence of the elliptic flow of charged particles in mid-pseudorapidity in mid-central Au+Au collisions at BES energies. The experimental data from the STAR Collaboration are taken from Ref. [13].

mainly contribute to $v_2(p_\mathrm{T})$ at high energies. We should be more careful to deal with the dynamics as $v_2(p_\mathrm{T})$ depend on models. We can see a better agreement with data at lower energies which implies that hadronic degrees of freedom are dominant. In Fig. 1 a mass ordering at $p_\mathrm{T} < 1.5$ GeV/c in UrQMD at all BES energies is also shown.

Fig. 2, 3, 4 show the calculated results for the p_T dependence of the elliptic flow v_2 of p and $\bar{\mathrm{p}}$, K^+ and K^-, π^+ and π^-, at BES energies, respectively. The experimental data from the STAR Collaboration are taken from Ref. [13]. And the difference in $v_2(p_\mathrm{T})$ between the particles and the corresponding antiparticles as a function of the transverse momentum p_T for Au+Au collisions at BES energies are also shown in Fig. 2, 3 and 4. From Fig. 2 we can clearly see that in UrQMD the v_2 for antiproton is larger than that for proton at all BES energies, which is in contradiction to the experimental result (see Fig. 2 subgraphics), and as the energy decreases, the deviation is larger. The opposite trend observed in experiment is therefore an indication that the strong coupling in heavy ion collision and the non equilibrium in transport process may need further understanding. From Fig. 3 we can see that in UrQMD the v_2 for K^- is slightly larger than that for K^+ at all BES energies and UrQMD can reasonably reproduce the experimental data(see subgraphics). In Fig. 4 the $v_2(p_\mathrm{T})$ values are almost identical for π^+ and π^- at 7.7 ~ 62.4 GeV. While in experiments, at lower energies, 7.7, 11.5 and 19.6 GeV, $v_2(\pi^-)$ is larger than $v_2(\pi+)$ for all p_T values[13]. Only at higher energies (27 ~ 62.4 GeV) UrQMD is compatible with experimental data.

The failure of the UrQMD to reproduce v_2 difference between particle and corresponding antiparticle might indicate that the model should incorporate interactions among quarks and gluons in the early collisions. In UrQMD the π^+ and π^- are mainly produced via decay from other particles which is different from the production of p and $\bar{\mathrm{p}}$, K^+ and K^-, the different production may lead to different behavior for p and $\bar{\mathrm{p}}$, K^+ and K^- between π^+ and π^-. Maybe the different production mechanism and rescattering process of hadrons lead to the different behavior of different particles. The v_2 for positive charge particle is smaller than that for corresponding negative charge particle probably due to the inhomogeneity of charge density with subsequent expansion of the created matter in which the negative particle feels repulsive force and the positive particle feels attractive force. The baryon chemical may be important in leading to the v_2 difference between proton and the antiproton.

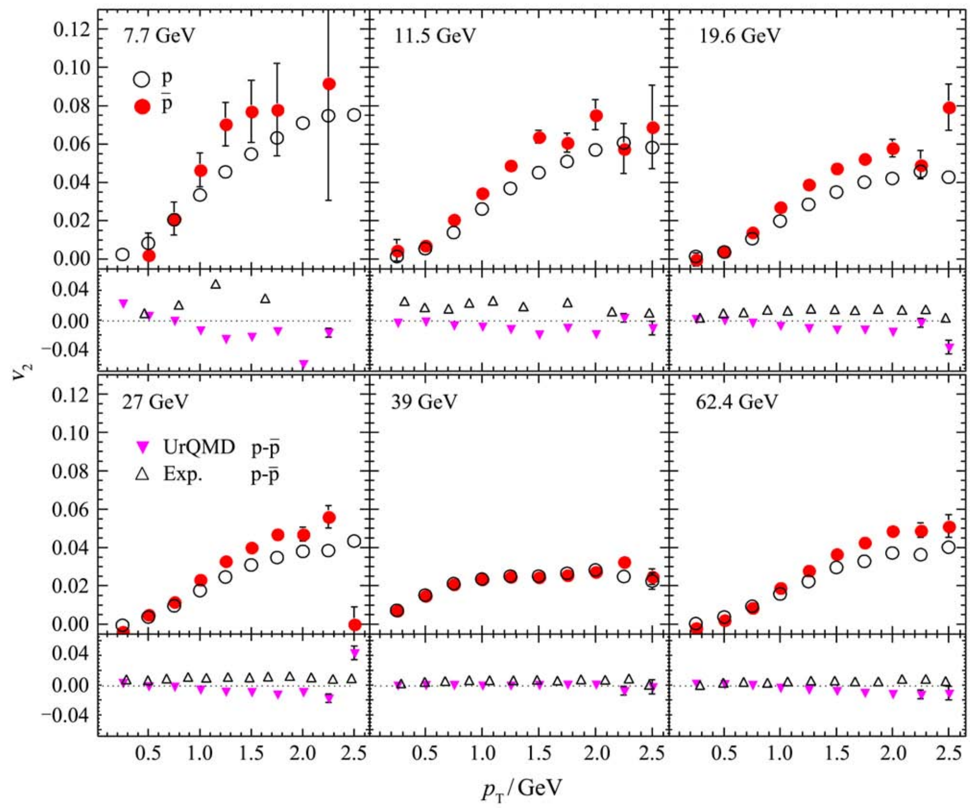

Fig. 2 The elliptic flow v_2 of protons and antiprotons and the difference in $v_2(p_\mathrm{T})$ between the particles and the corresponding antiparticles as a function of the transverse momentum p_T for Au+Au collisions at BES energies. The experimental data from the STAR Collaboration are taken from Ref. [13].

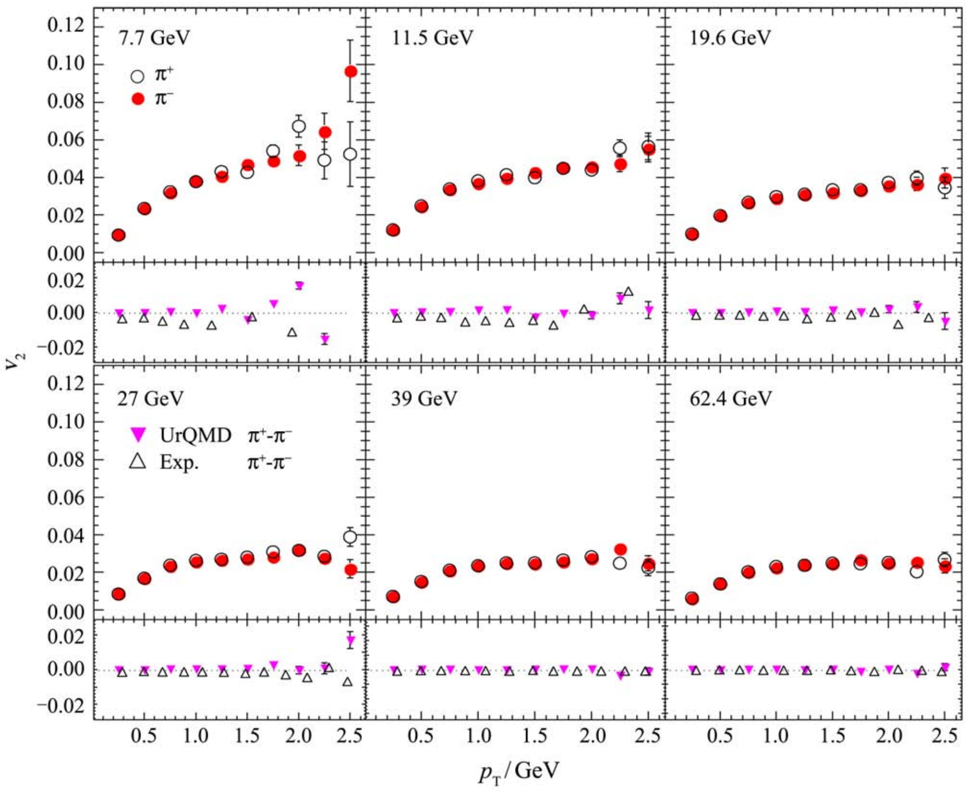

Fig. 3　The elliptic flow v_2 of K^+ and K^- and the difference in $v_2(p_T)$ between the particles and the corresponding antiparticles as a function of the transverse momentum p_T for Au+Au collisions at BES energies. The experimental data from the STAR Collaboration are taken from Ref. [13].

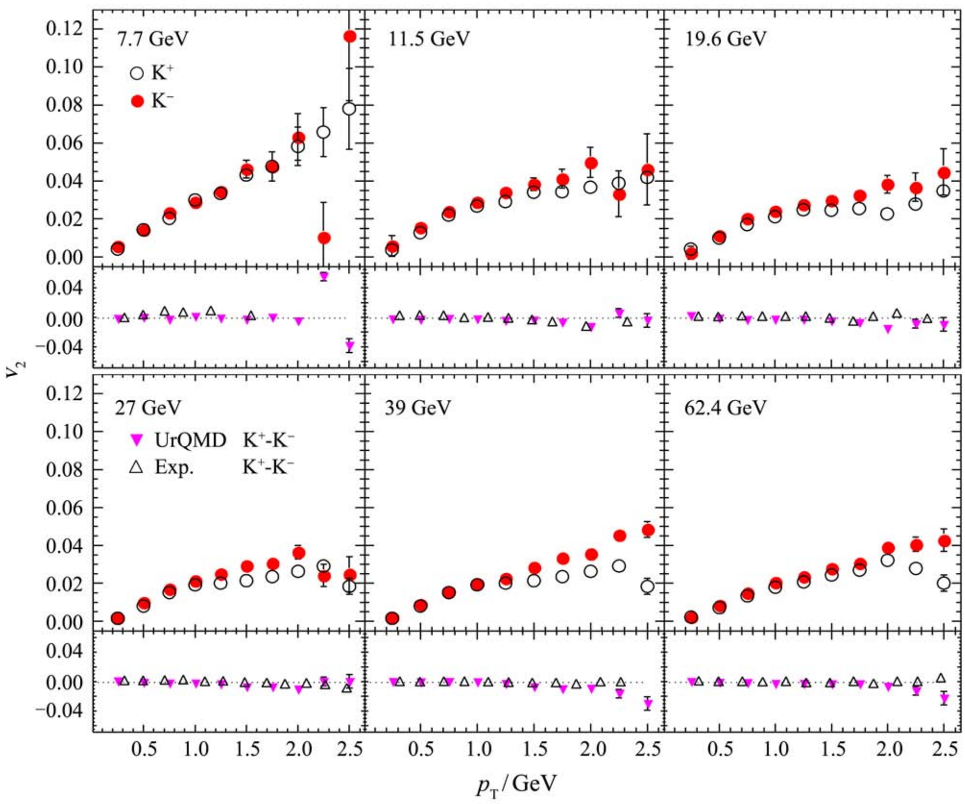

Fig. 4　The elliptic flow v_2 of π^+ and π^- and the difference in $v_2(p_T)$ between the particles and the corresponding antiparticles as a function of the transverse momentum p_T for Au+Au collisions at BES energies. The experimental data from the STAR Collaboration are taken from Ref. [13].

4 Summary

We have investigated elliptic flow v_2 of charged particles, such as protons, antiprotons, K^+, K^-, π^+ and π^-, in mid-pseudorapidity in mid-central Au+Au collisions at BES energies in UrQMD model. And the difference in $v_2(p_T)$ between the particles and the corresponding antiparticles as a function of the transverse momentum p_T for Au + Au collisions at BES energies are also analyzed. We compared the calculation results with experimental ones. We find that the UrQMD model generally underestimates the $v_2(p_T)$ values at BES energies. The v_2 for K^- is larger than that for K^+ at all BES energies in UrQMD. The $v_2(p_T)$ values are almost identical for π^+ and π^- at $7.7 \sim 62.4$ GeV. While in experiments, at lower energies, 7.7, 11.5 and 19.6 GeV, $v_2(\pi^-)$ is larger than $v_2(\pi^+)$ for all p_T values. We can clearly see that in UrQMD the v_2 for antiproton is larger than that for proton at all BES energies, which is in contradiction to the experimental result. The opposite trend observed in experiment is therefore an indication of oversimplification of the model we used. More realistic theoretical and more detailed experimental studies are needed for understanding the different behavior of elliptic flow of particles and antiparticle and other puzzles.

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UrQMD模型中对质心能量7.7～62.4 GeV下正反粒子椭圆流的差异研究

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摘要： 利用UrQMD-3.3p1模型模拟了在质心能量$\sqrt{s_{\rm NN}}=7.7$, 11.5, 19.6, 27, 39和62.4 GeV的Au+Au碰撞，在中心快度区域分析了质子，π^+，$\rm K^+$以及它们相应的反粒子的椭圆流。分析了粒子与相应的反粒子的v_2差值随横动量$p_{\rm T}$的变化。分析结果表明，在UrQMD模型中在整个BES能区$\rm K^-$的v_2值大于$\rm K^+$的。在能区7.7～62.4 GeV π^+和π^-的$v_2(p_{\rm T})$值几乎相同。然而实验上在低能区7.7, 11.5和19.6 GeV, 在所考察的$p_{\rm T}$值范围内$v_2(\pi^-)$大于$v_2(\pi^+)$。能清楚看到在UrQMD模型中在整个BES能区反质子的v_2大于质子的，这与实验结果相反。理论结果与实验数据相反，表明我们还需要不断深化对重离子碰撞的强耦合性和输运过程的非平衡性的理解。

关键词： 椭圆流；重离子碰撞；UrQMD模型

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