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# Freeze-out and anisotropic flow in microscopic models

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**Abstract** It appears that in microscopic calculations hadrons are continuously emitted from the whole reaction volume. Different species decouple at different times. At RHIC energies significant fractions of both mesons and baryons are emitted from the surface region within the first two fm/c. The hadrons contribute differently to the formation and evolution of the anisotropic flow, which can be decomposed into three components: (i) flow created by hadrons emitted from the surface at the onset of the collision; (ii) flow produced by jets; (iii) hydrodynamic flow. Due to these features, e.g., the elliptic flows of mesons and baryons have different transverse momentum dependences. Comparison with experimental data reveals that centrality, rapidity, and transverse momentum dependences of the anisotropic flow are reproduced, at least qualitatively, by the microscopic models.

**Key words** ultrarelativistic heavy-ion collisions • elliptic flow • freeze-out of particles • Monte-Carlo quark-gluon string model

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## Introduction

Ultrarelativistic heavy-ion collisions are at present the only tools to study properties of dense and hot nuclear matter experimentally. The main aim of the experiments at RHIC BNL and at coming LHC CERN is to reveal new phenomena attributed to highly anticipated formation of quark-gluon plasma (QGP) and its subsequent hadronization. Anisotropic flow is one of the most promising signals which are extremely sensitive to creation even a small amount of QGP. Recall, that the collective flow of nuclear matter in azimuthal plane can be decomposed into isotropic radial component and anisotropic one by means of Fourier expansion of the particle invariant distribution [24]

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}\frac{d^3N}{dp_t^2\,dy}\left[1 + 2\sum_{n=1}^{\infty} \upsilon_n \cos(n\phi)\right] \quad (1)$$

where $\phi$ is the azimuthal angle between the transverse momentum of the particle and the reaction plane, and $p_t$ and $y$ is the transverse momentum and the rapidity, respectively. The sum in the r.h.s. of Eq. (1) represents the anisotropic flow. Its first two harmonic coefficients are called directed flow

$$\upsilon_1 \equiv \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_t} \right\rangle \quad (2)$$

and elliptic flow, respectively,

(3) $$\upsilon_2 \equiv \langle \cos 2\phi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

The latter measures the eccentricity of the particle distribution in the momentum space in the coordinate system with the $z$-axis directed along the beam and the impact parameter axis labeled as $x$.

Anisotropic flow is very sensitive to the equation of state (EOS) of nuclear matter. The vanishing of pressure gradients in the mixed phase of first order quark-hadron phase transition, known as the softening of the EOS, should result in deviations of the directed flow of nucleons from the linear behavior [17]. Also, the large value of the elliptic flow measured in RHIC experiments may indicate very short equilibration times and large initial pressure gradients, both attributed to properties of a strongly interacting matter. Therefore, the study of the formation and evolution of anisotropic flow remains one of the top-priority topics of the heavy-ion programme.

The development of anisotropic flow is closely related to the freeze-out of particles. The microscopic model calculations [12, 13] show the absence of sharp freeze-out of particles in relativistic heavy-ion collisions. In contrast to assumptions of hydrodynamic models, the expanding fireball in microscopic models can be rather treated as a core consisting of still interacting hadrons, and a halo, which contains particles already decoupled from the system. The order of the freeze-out of different species seems to be the same for energies ranging from AGS to RHIC: 1 – pions, 2 – kaons, 3 – lambdas, 4 – nucleons. The aim of this paper is to study consequences of the continuous freeze-out to the evolution of anisotropic flow of hadrons.

## Directed and elliptic flow

For our study, we employ the quark-gluon string model (QGSM) [3, 4, 20], which is a microscopic model based on the Gribov reggeon theory (GRT) [18, 19] of hadronic and nuclear interactions at high energies. The main advantage of the GRT is the fulfillment of unitarity conditions in $s$- and $t$-channel for multiparticle processes. The QGSM incorporates also the string fragmentation, resonance formation, and hadronic rescattering. The latter implies that the decay products of a string – stable hadrons and their resonances – can further interact with other hadrons.

### Directed flow at midrapidity

Directed flow of hadrons is developing almost till the end of the fireball evolution in microscopic models [9, 21]. Its rapidity distribution has the following feature: at incident energies below 10 AGeV, the flow of nucleons grows linearly with increasing rapidity between the target and projectile fragmentation regions (normal flow), whereas the flow of pions decreases in the same rapidity range (antiflow behavior). The one-fluid hydrodynamic model indicates [10] that deviations from the straight line behavior can be caused only by the creation of QGP. However, all microscopic models [8, 11, 16, 22, 23] demonstrate a presence of the so-called wiggle structure in the directed flow of nucleons, first mentioned for very peripheral Au+Au collisions at AGS energy in [8]. Experimentally, the wiggle structure of directed flow of protons was observed in peripheral Pb+Pb collisions at SPS energy [2]. As to RHIC energies, the directed flow of charged particles is essentially zero at $|y| \leq 2$ in most microscopic models. In QGSM calculations the flow has negative slope. Figure 1 displays the $v_1(\eta)$ distribution of charged hadrons in Au+Au collisions at $\sqrt{s}$ = 200 AGeV. Here the PHOBOS Collaboration data [7] are compared to the QGSM calculations for different centrality bins. One can see that though the data seem to favor the antiflow elongation, the measured signal is quite weak, and relatively large systematic error bars do not permit to make more definite conclusions. We are awaiting new data to resolve the ambiguity.

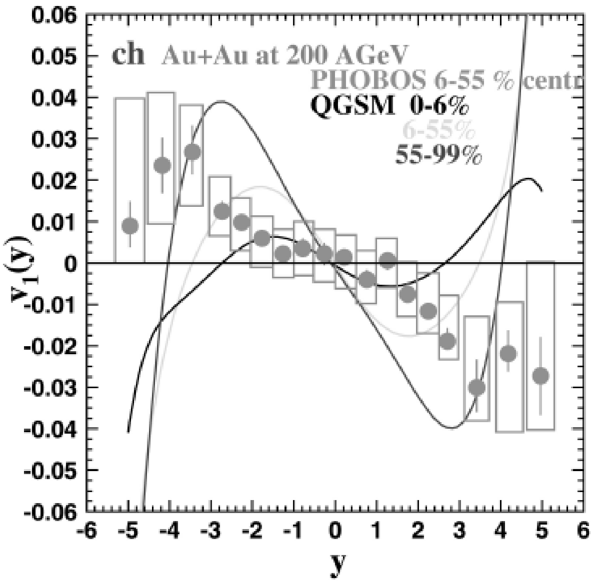


**Fig. 1.** Directed flow of charged particles in Au+Au collisions at AGeV. Boxes denote PHOBOS data [7] and lines – QGSM calculations.

### Development of elliptic flow

To investigate the formation of elliptic flow, ca. $20{*}10^3$ gold-gold collisions with the impact parameter $b$ = 8 fm were generated at $\sqrt{s}$ = 130 AGeV. According to previous studies [1, 26, 27] the elliptic flow of charged particles is close to its maximum at this impact parameter, and the multiplicity of secondaries is still quite high. To demonstrate the absence of sharp particle freeze-out at RHIC energies, the $dN/dt$ distributions of charged hadrons, pions, nucleons and lambdas, which are decoupled from the system after their last elastic or inelastic interaction, are shown in Fig. 2a. One can see that a substantial part of hadrons leaves the fireball immediately after their production within the first two fm/c, in stark contrast with heavy-ion reactions at lower energies [12, 13].

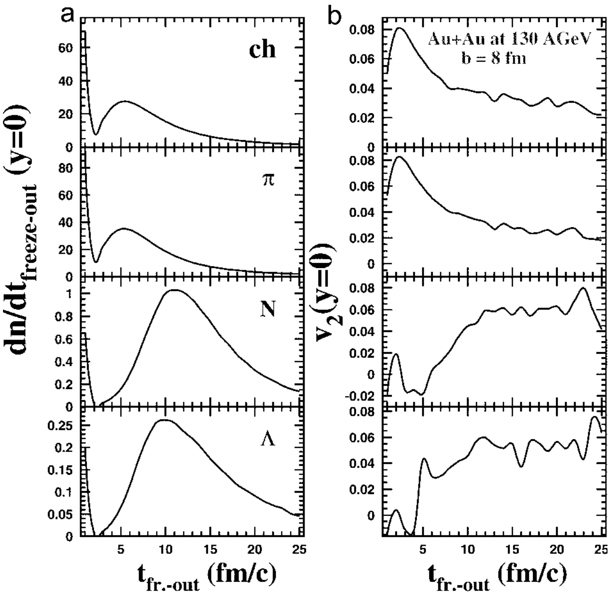


**Fig. 2.** a – *dN/dt* distribution vs. time of their last interaction, and b – elliptic flow of these particles for Au+Au collisions with $b$ = 8 fm at AGeV.

Elliptic flow carried by these hadronic species is presented in Fig. 2b. The baryonic and mesonic components are completely different: pions emitted from the surface of the expanding fireball within the first few fm/c carry the strongest flow, while later on the flow of pions is significantly reduced. In contrast to pions, the baryon fraction acquires stronger elliptic flow during the subsequent evolution of the system. Clearly, the elliptic flows of pions and nucleons cannot be produced simultaneously after $t \approx 15$ fm/c within the same fireball. Where these particles come from? Figure 3 depicts the contours of the $d^2N/dydt$ and $d^2N/dzdt$ distributions over rapidity and time, and longitudinal coordinate and time, respectively. In right panels one can see that for the central region with $|z| \le 15$ fm the emission of hadrons takes place till $t^\pi \approx 15$ fm/c for pions and $t^N \approx 25$ fm/c for nucleons.

Most pions are emitted in the central rapidity window $|y| \le 2$ from the overlapping almond-shaped zone. As the radial symmetry of this region is restored, their elliptic flow becomes weaker. This part dominates during the first 10–14 fm/c after the beginning of the reaction, when the rapidity spectra of pions look like emission from a thermal source. Nucleons are coming from the overlapping zone as well and from the regions of flying away spectators. This circumstance explains why the $v_2^N$ maintains its strength after $t \approx 12$ fm/c. Thus, the elliptic flow of hadrons has a multicomponent structure, namely, (i) hydrodynamic flow, and (ii) non-hydrodynamic flow caused by the particle splash from the surface area, by the non-uniform emission of hadrons from the spectators, and by the non-uniform absorption of hadrons in spatially asymmetric dense matter.

Model predictions for the rapidity distribution of the elliptic flow of hadrons at both RHIC energies, 130 AGeV and 200 AGeV, can be found, e.g., in [14, 25–27]. The time scales of the elliptic flow development at these two energies are almost identical. In Fig. 4 model calculations are compared to the experimental data measured by PHOBOS collaboration [6]. Here, the elliptic flow of charged particles for the collisions with centralities 0–15% (0.0 fm $\le b <$ 2.3 fm), 15–25% (2.3 fm $\le b <$ 6.5 fm), and 25–50% (6.5 fm $\le b <$ 9.2 fm) is presented together with the resulting flow in minimum bias events. The model reproduces the measured signal pretty well, including the nearly flat distribution at $|\eta| \le 2$ and quick fall of the elliptic flow at $|\eta| \ge 2$. The only discrepancy arises in semiperipheral collisions at midrapidity range, where the data are approximately 15% above the model results. The double-hump structure of the elliptic flow in the QGSM stems from the dynamics of particle rescattering, i.e. the larger the number of hadronic collisions, the stronger the flow (see [15] for the details). The measured elliptic flow at RHIC violates this obvious tendency. Namely, the PHOBOS $v_2(\eta)$ data demonstrate a clear peak at midrapidity, whereas their $dN/d\eta$

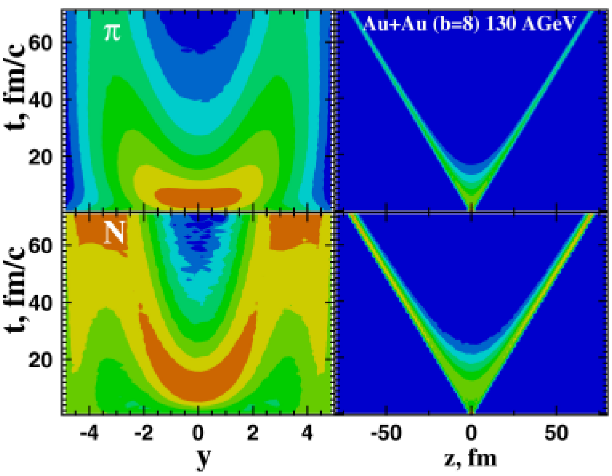


**Fig. 3.** Rapidity and $z$-distribution of the final state pions (upper panels) and nucleons (bottom panels) vs. their last interaction points.

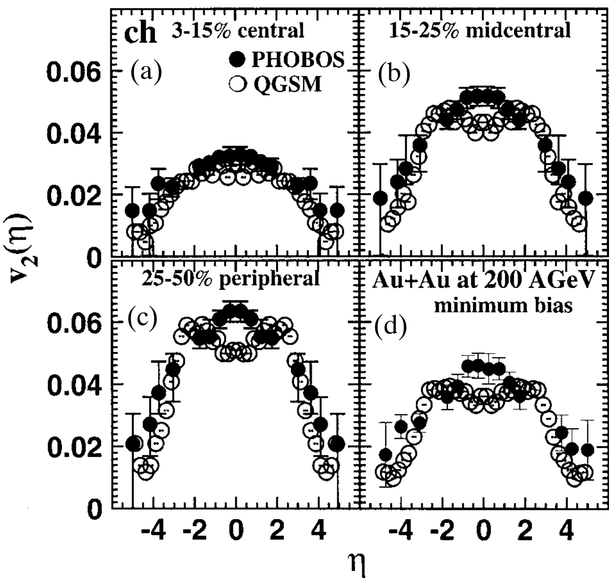


**Fig. 4.** Distribution of charged particles in Au+Au collisions at AGeV for (a), (b), (c), and (d) minimum bias events. Full symbols represent data [6], open symbols denote model calculations.

distribution [5] has a plateau within three units of pseudorapidity. This problem should be clarified in the future.

## Conclusions

In summary, the features of the formation and development of anisotropic flow in the microscopic quark-gluon string model can be stated as follows. Directed and elliptic flows of hadrons are formed not only during the first few fm/c, but also during the whole evolution of the system because of continuous freeze-out of particles. Time evolutions of the mesonic flow and baryonic flow are quite different. Directed flow of nucleons at RHIC has a characteristic wiggle structure at midrapidity. Pions are emitted mainly from the overlapping almond-shaped zone of the reaction. As the symmetry of the almond is restored, their elliptic flow decreases. Nucleons are coming both from the overlapping area and from the spectator domains. Freeze-out dynamics for baryons and mesons is different and, therefore, development of particle collective flow should not be studied independently of the freeze-out picture. The general trend in particle flow formation in microscopic models at ultrarelativistic energies is that the earlier mesons are frozen, the weaker their elliptic flow. In contrast, baryons frozen at the end of the system evolution have stronger flow.

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