Anisotropic flow of strange particles in heavy ion collisions at RHIC energies

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Abstract. Anisotropic flow of \( K \)'s, \( \bar{K} \)'s, and \( \Lambda \)'s is studied in heavy ion collisions at SPS and RHIC energies within the microscopic quark-gluon string model. At SPS energy the directed flow of kaons differs considerably at midrapidity from that of antikaons, while at RHIC energy kaon and antikaon flows coincide. The change is attributed to formation of dense meson-dominated matter at RHIC, where the differences in interaction cross-sections of hadrons become unimportant. The directed flows of strange particles, \( v_1 \), have universal negative slope at \(|y| \leq 2\) at RHIC. The elliptic flow of strange hadrons is developed at midrapidity at times \( 3 \leq t \leq 10\) fm/c. It increases almost linearly with rising \( p_t \) and stops to rise at \( p_t \geq 1.5\) GeV/c reaching the same saturation value \( v_2 \approx 10\% \) in accord with experimental results.

1. Introduction

The transverse collective flow of particles is at present one of the most intensively studied characteristics of heavy-ion collisions [1], because the flow is directly linked to the equation of state (EOS) of the system. If even a small amount of the quark-gluon plasma (QGP) is formed in the course of the collision, it would lead to a reduction of pressure and a softening of the EOS that can be detected experimentally. To study the properties of transverse particle flow the method of Fourier series expansion [2] has been proved to be very useful:

\[
E \frac{d^2N}{dp} = \frac{d^2N}{2\pi p dp dy} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n\phi) \right]. \tag{1}
\]

Here \( p_t \), \( y \), and \( \phi \) are the transverse momentum, rapidity, and the azimuthal angle of a particle, respectively. The unity in square brackets represents the isotropic radial flow, while the other terms are refer to anisotropic, directed \( v_1 = \langle \cos \phi \rangle \) and elliptic \( v_2 = \langle \cos (2\phi) \rangle \), flow. The idea that the elliptic flow can carry important information about the early stage of heavy-ion collisions has been discussed first in Ref. [3]. This suggestion is supported by macroscopic hydrodynamic and microscopic transport simulations, which show that elliptic flow saturates quite early [4], while directed flow develops almost until the stage of final interactions [5]. However, the directed flow of hadrons with high transverse momentum can be used as a probe of hot and dense phase of the collision [6] due to the early freeze-out times of these particles.
In the present paper we are studying the anisotropic flow of kaons, antikaons, and lambdas produced in lead-lead and gold-gold collisions at \( E_{\text{lab}} = 160 \text{ AGeV} \) (SPS) and \( \sqrt{s} = 130 \text{ AGeV} \) (RHIC), respectively. For the study the microscopic cascade quark-gluon string model (QGSM) [10], based on Gribov-Regge theory accomplished by a string phenomenology of particle production in inelastic hadron-hadron collisions, is employed. The model successfully describes the elliptic flow of charged particles at RHIC [11] measured recently [12], as well as other characteristics.

2. Anisotropic flow at SPS and RHIC

Time evolution of directed and elliptic flow of strange particles in minimum bias Pb+Pb collisions at SPS is shown in Fig. 1. Here the anisotropic flow is calculated at early, \( t = 3 \text{ fm/c} \) and \( t = 10 \text{ fm/c} \), and at the final stage of the reaction. To avoid ambiguities, all resonances in the scenario with early freeze-out were allowed to decay according to their branching ratios. At early stages of the collision directed flow of all strange particles is oriented in the direction of normal flow similar to that of nucleons. At this stage the matter is dense, mean free paths of particles are short, and similarities in hadron production and rescattering dominate over inequalities caused by different interaction cross-sections. Later on the system becomes more dilute. Due to larger interaction cross-sections of antikaons with other hadrons, the directed flow of these particles changes the orientation from a weak normal to strong antiflow.

Figure 1. Time evolution of directed \( v_1(y) \) and elliptic \( v_2(y) \) flow of kaons, antikaons, and lambdas in minimum bias Pb+Pb collisions at SPS.

Elliptic flow of \( K^\prime \)s, \( \bar{K}^\prime \)s and \( \Lambda \)'s is close to zero at \( t = 3 \text{ fm/c} \), i.e., the particle distribution is isotropic in the transverse plane. The resulting elliptic flow of strange particles at SPS is positive. This feature can be explained by secondary rescattering in the spatially anisotropic matter that lead to increase of the elliptic flow along the impact parameter axis. Note that at midrapidity the elliptic flow is formed at \( t \leq 10 \)
flow of $K$'s and $\Lambda$'s in HICs at RHIC at $3\text{ fm/c}$, that quantitatively agrees with the estimates made in [3].

![Figure 2.](image)

Time evolution of the anisotropic flow of strange particles at RHIC is depicted in Fig. 2. At midrapidity directed flow of $K$'s, $\overline{K}$'s, and $\Lambda$'s is nearly zero at $t = 3\text{ fm/c}$, but it changes to strong antiflow at $t \geq 10\text{ fm/c}$ with the similar slopes for all strange hadrons. The effect is traced to nuclear shadowing which can mimic formation of the QGP (see [3]) at ultra-relativistic energies. Final elliptic flow of all particles clearly shows the in-plane orientation. Directed and elliptic flows of $K$'s and $\overline{K}$'s coincide within the statistical error bars. This is attributed to the formation of dense baryon-dilute matter, where the difference in interaction cross sections of particles play a minor role.

Figure 3 presents the $p_T$-dependence of the elliptic flow of strange hadrons at RHIC. The flow is close to zero for hadrons with $p_T \leq 0.25\text{ GeV/c}$, then rises linearly up to $v_2^K(p_T) \approx 10\%$ irrespective of the hadron mass within the interval $0.25 \leq p_T \leq 1.5\text{ GeV/c}$, and saturates at $p_T \geq 1.5\text{ GeV/c}$ in accord with the experimental data [14]. This behaviour can be explained by the interplay between the flow of high-$p_T$ particles, emitted at the onset of the collision, and the hydro-type flow of particles, which gained their high $p_T$ in secondary interactions.

3. Conclusions

The results may be summarised as follows. (1) The directed flow of kaons $v_1^K(y)$ produced in minimum bias Pb+Pb collisions at SPS is found to be close to zero in the midrapidity range, while the $v_1^K(y)$ has a linear antiflow slope because of different interaction cross sections and large absorption cross section of antikaons with baryons. (2) In heavy ion collisions at RHIC a dense meson-dominated matter is produced, and the directed flow of $K$’s becomes similar to that of $\overline{K}$’s. (3) The directed flows of $K$’s, $\overline{K}$’s, and $\Lambda$’s have universal negative slope at $|y| \leq 2$ at RHIC. (4) The elliptic flow
Flow of $K$’s and $\Lambda$’s in HICs at RHIC

Figure 3. Transverse momentum dependence of the elliptic flow of strange particles in the whole rapidity (a) and in central rapidity interval (b) in minimum bias $Au+Au$ collisions at RHIC. Data taken from [14].

of strange particles is built up at midrapidity at $3 \leq t \leq 10$ fm/c both at SPS and at RHIC. At RHIC it increases linearly with rising $p_T$ and reaches saturation value $v_2^{K,K,\Lambda}(p_T) \approx 10\%$ at $p_T \geq 1.5$ GeV/c.

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