Charged hadron spectra and anisotropic flows in O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV using the UrQMD model

Спектры и анизотропные потоки заряженных адронов в O+O, Kr+Kr и Xe+Xe столкновениях при энергии $\sqrt{s_{NN}} = 6$ ГэВ в модели UrQMD

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В ядерных столкновениях спектры поперечного импульса заряженных адронов несут информацию об условиях на стадии кинетического вымораживания. Анализ этих спектров позволяет количественно определить термодинамические параметры системы. Измерение анизотропных потоков даёт возможность исследовать коллективное поведение системы и её эволюцию от начальной пространственной анизотропии до конечных корреляций в импульсном пространстве.

В данной работе используется модель ультрарелятивистской квантовой молекулярной динамики (UrQMD) для исследования спектров поперечного импульса (p_T) и коэффициентов анизотропного потока (v_n) заряженных адронов в столкновениях O+O, Kr+Kr и Xe+Xe при энергии $\sqrt{s_{NN}} = 6$ ГэВ, что соответствует физической программе будущего эксперимента SPD на коллайдере NICA. Температура кинетического замораживания и скорость радиального потока извлекаются из этих спектров с использованием модели взрывной волны. Эллиптический (v_2) и треугольный (v_3) потоки представлены как функции центральности столкновений. Проведено систематическое сравнение термических и коллективных свойств в различных сталкивающихся системах. Полученные результаты будут способствовать пониманию свойств сильно взаимодействующей материи в энергетическом диапазоне коллайдера NICA.

The transverse momentum spectra of charged hadrons reflect the kinetic freeze-out conditions in nuclear collisions. Analysis of these spectra enables quantitative extraction of the system's thermodynamic parameters. The anisotropic flows probe the system's collective behavior and its evolution from initial spatial anisotropy to final momentum-space correlations.

In this work, the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model is employed to investigate transverse momentum (p_T) spectra and anisotropic flow coefficients (v_n) of charged hadrons in O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV, addressing the physics program of the upcoming SPD experiment at NICA. The kinetic freeze-out temperature and radial flow velocity are extracted from these spectra using blast-wave parameterization. The elliptic (v_2) and triangular (v_3) flows are presented as functions of the collision centrality. A systematic comparison of thermal and collective properties across different colliding systems is performed. The obtained results will contribute to understanding strongly interacting matter in the NICA energy regime.

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Introduction

Mapping the quantum chromodynamics (QCD) phase diagram is among the primary objectives of heavy-ion collision experiments [1]. Of particular interest is the high-baryon density region of this phase diagram, accessible at NICA energies, where a first-order phase transition and critical point are predicted. In this study, we focus on two key observables to probe this region.

Transverse momentum spectra of identified hadrons provide information about the system at the kinetic freeze-out stage, when elastic interactions between particles cease [2, 3]. The shape of these spectra allows extracting the kinetic freeze-out temperature, $T_{\rm kin}$, and the average transverse radial flow velocity, $\langle\beta_T\rangle$, which characterizes the collective expansion of the fireball created in the collision. Anisotropic flow coefficients, particularly elliptic flow v_2 and triangular flow v_3, provide crucial insights into the early-stage evolution and transport properties of the created matter [4]. They arise from the conversion of initial spatial anisotropy into final momentum-space anisotropy via collective interactions, serving as a sensitive probe of the system's equation of state and viscosity.

In this paper, we present the results on calculating p_T-spectra of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, and the anisotropic flows of charged hadrons in O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV using the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model [5].

Data analysis

Collisions of oxygen, krypton, and xenon nuclei at $\sqrt{s_{NN}} = 6$ GeV are simulated using the UrQMD 3.4 model. Data sets of 71 million events for O+O and 91 million events each for Kr+Kr and Xe+Xe collisions are used in this analysis. Centrality classes are determined as percentiles of the reference multiplicity distribution. The reference multiplicity is defined as the number of charged particles within the pseudorapidity region $|\eta|< 1.0$ having transverse momentum $p_T > 0.15$ GeV/c. This kinematic window ensures the uniform acceptance and optimal reconstruction efficiency of charged particle tracks in the SPD experiment. Figure 1 shows the reference multiplicity distributions and the centrality classes for the O+O, Kr+Kr, and Xe+Xe systems.

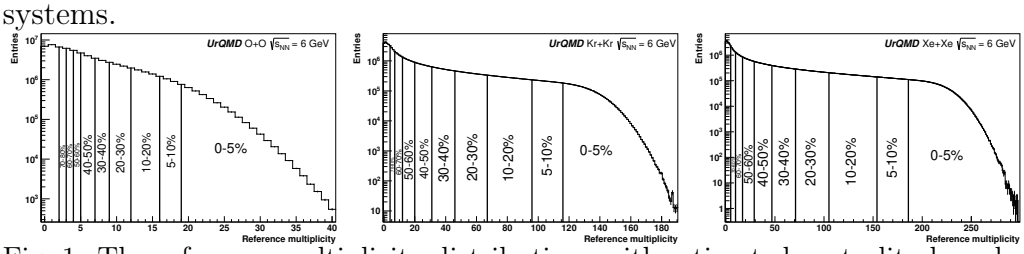


Fig. 1. The reference multiplicity distributions with estimated centrality boarders for O+O, Kr+Kr and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV

The transverse momentum spectra of identified hadrons ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) within |y| < 0.1 are analyzed in eight centrality intervals, covering the range from central (0-5%) to peripheral (60-70%) collisions. For the O+O system, the analysis extends to the 50-60% centrality class. These species are selected for their high yields and diverse masses, enabling a clear separation of thermal and collective effects. The rapidity requirement |y|<0.1 is applied to ensure longitudinal boost-invariance of the spectra and to focus the analysis on the region where the assumption of local thermal equilibrium is most robust.

To extract the kinetic freeze-out parameters, a simultaneous fit of the identified hadron spectra is performed using the blast-wave model [2]. In this model, the fireball is described as a locally thermalized source undergoing collective transverse expansion with a common velocity profile. Within this parametrization, the p_T-spectrum of particles is given by

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right), \qquad (1)$$

where $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass of a hadron, I_0 and K_1 are the modified Bessel functions. The flow profile $\rho(r)$ is described as $\rho(r) = \tanh^{-1}\beta_T = \tanh^{-1}[(r/R)^n \beta_S]$, where β_T is the transverse flow velocity at radius r, β_S is the surface velocity, R is the radius of the fireball, and n is the exponent parameterizing the flow profile. The average transverse radial flow velocity $\langle\beta_T\rangle$ can then be calculated as $\langle\beta_T\rangle = \frac{2}{2+n}\beta_S$. The extracted kinetic freeze-out parameters are sensitive to the p_T ranges used for fitting. In this study, the simultaneous fit of the spectra is performed in the ranges 0.5–1.0 GeV/c for pions, 0.35–1.1 GeV/c for kaons, and 0.6–1.1 GeV/c for (anti)protons. These ranges are kept consistent across all colliding systems. Figure 2 shows the blast-wave model fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ transverse momentum spectra in 0–5% central O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV.

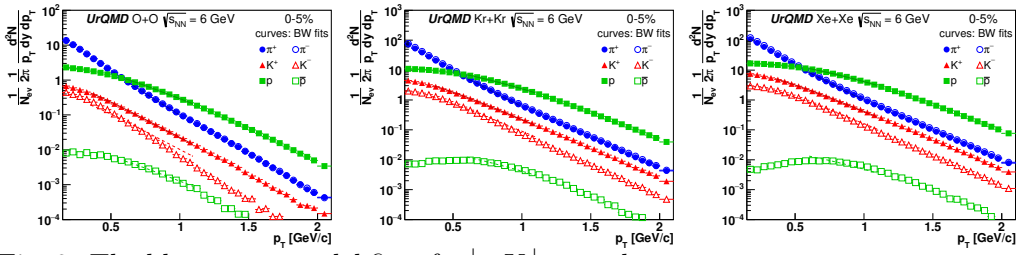


Fig. 2. The blast-wave model fits of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ transverse momentum spectra in 0–5% central O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV

The azimuthal anisotropy is quantified through the Fourier decomposition of the particle distribution: $dN/d\phi \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$, where ϕ is the azimuthal angle of the particle, Ψ_n is the n-th order event plane angle, and v_n are the anisotropic flow coefficients [6, 7]. The n-th order flow coefficient is calculated as $v_n = \langle\cos[n(\phi - \Psi_n)]\rangle$, where the averaging is performed over all particles in all events. In this analysis, the anisotropic flow coefficients v_2 and v_3 are calculated for charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) using the sub-event plane method with $\Delta\eta$ gap 0.1. Particles are required to have transverse momenta $0.15 < p_T < 2.0$ GeV/c and pseudorapidity within the region $|\eta| < 1.0$. The anisotropic flow coefficients are calculated as a function of collision centrality.

Results and discussion

The extracted kinetic freeze-out parameters for all the colliding systems in different centrality classes are presented in Figure 3. In central collisions, a significantly lower value is observed for O+O compared to the larger Kr+Kr and Xe+Xe systems. The decrease of $\langle\beta_T\rangle$ with increasing centrality indicates a more rapid collective expansion in central collisions. The kinetic freeze-out temperature shows a different behavior. An increase of $T_{\rm kin}$

from central to peripheral collisions is observed in Kr+Kr and Xe+Xe systems, with the centrality dependence of $T_{\rm kin}$ in O+O collisions being weak or even absent. This may be attributed to the smaller size of the O+O system. The value of $T_{\rm kin}$ itself is found to be approximately the same across all three colliding systems within the uncertainties.

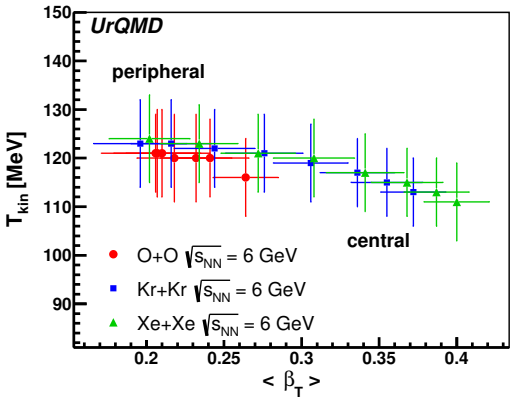


Fig. 3. The kinetic freeze-out parameters, T_{kin} and $\langle\beta\rangle$, in O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}}$ = 6 GeV for different centralities

The elliptic flow of charged hadrons as a function of centrality is presented in the top panels of Figure 4. Centrality dependence of the elliptic flow is observed for all colliding systems. The v_2 coefficient generally increases from central to peripheral collisions, while exhibiting a non-monotonic trend. Furthermore, the absolute magnitude of v_2 in O+O collisions is notably large. These observations suggest significant non-flow contributions, which are particularly pronounced in small colliding systems and require further investigation.

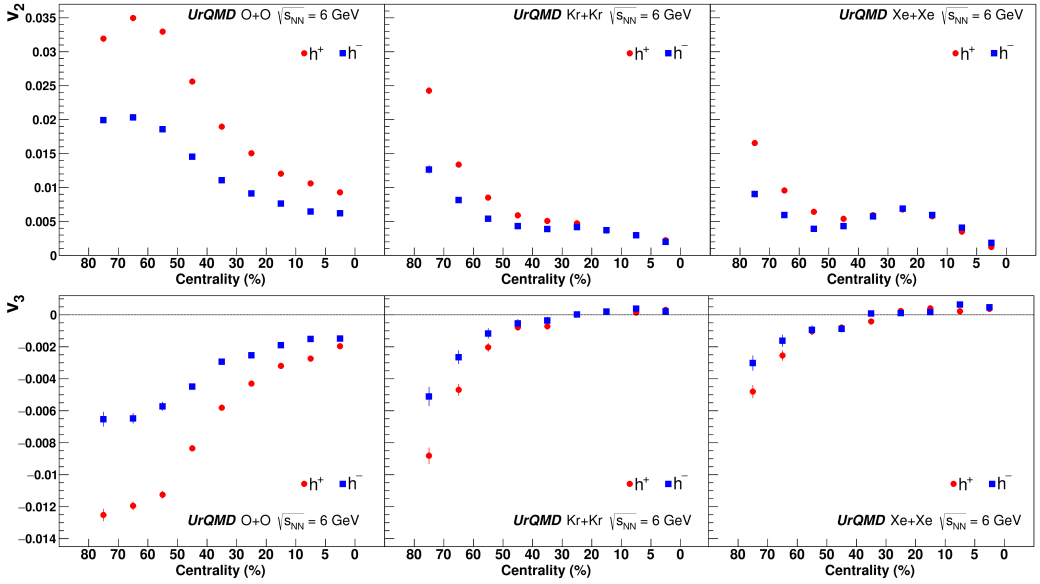


Fig. 4. Elliptic flow (top panels) and triangular flow (bottom panels) of charged hadrons as a function of centrality in O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}} = 6$ GeV

The triangular flow of charged hadrons, presented in the bottom panels of Figure 4, also exhibits a clear centrality dependence, with its magnitude increasing towards peripheral collisions. The values of triangular flow v_3 are predominantly negative across all systems and centralities. This systematic trend requires further detailed investigation.

Conclusions

In this work, we presented a systematic study of O+O, Kr+Kr, and Xe+Xe collisions at $\sqrt{s_{NN}}$ = 6 GeV using the UrQMD 3.4 model. The average radial flow velocity $\langle\beta\rangle$ decreases from central to peripheral collisions, with significantly lower values observed in central O+O collisions compared

to larger systems. The kinetic freeze-out temperature $T_{\rm kin}$ increases from central to peripheral collisions in Kr+Kr and Xe+Xe systems, while showing a weak centrality dependence in O+O collisions.

The anisotropic flow coefficients v_2 and v_3 also exhibit a clear centrality dependence in O+O, Kr+Kr, and Xe+Xe collisions, with the magnitudes of v_2 and v_3 mostly increasing from central to peripheral collisions. The non-monotonic behavior of their centrality dependencies and unexpectedly large v_2 signals in O+O collisions may be attributed to the significant non-flow contributions. The triangular flow v_3 is found to be consistently negative across all colliding systems. These observations require further investigation.

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