Properties of $\rho(770)^0$, $K^*(892)$, $\phi(1020)$, $\Sigma(1385)^\pm$, $\Lambda(1520)$ and $\Xi(1530)^0$ resonances in heavy-ion collisions at a center of mass energy of $\sqrt{s_{NN}} = 4$-11 GeV and their reconstruction using the MPD detector at NICA

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Abstract. The short-lived hadronic resonances are used to study properties of the hot and dense medium produced in relativistic heavy-ion collisions. Due to their short lifetimes, the resonance yields and masses measured in the hadronic channels are sensitive to rescattering and regeneration effects in the hadronic phase. The measurement of resonances is foreseen in the physical program of the MPD experiment at NICA in heavy-ion collisions at $\sqrt{s_{NN}} = 4$-11 GeV, in the range of energies where extensive measurements of resonances are not experimentally available. In this contribution, we explore the sensitivity of the $\rho(770)^0$, $K^*(892)$, $\phi(1020)$, $\Sigma(1385)^\pm$, $\Lambda(1520)$, and $\Xi(1530)^0$ resonances measured in the hadronic decay channels to different stages of the heavy-ion collisions at NICA energies and report the feasibility studies for the reconstruction of resonances in the MPD setup

1. Introduction

The short-lived resonances such as $\rho(770)^0$, $K^*(892)$, $\phi(1020)$, $\Lambda(1520)$, $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ are copiously produced in heavy-ion collision at GeV-energies and carry a wealth of information about reaction dynamics, strangeness production phenomenon and hadronization mechanisms. First studies of resonances production were done at SPS [1], then the precision increased towards RHIC [2] and LHC [3]. The future MPD experiment at the NICA facility [4] will provide the means to study resonances properties in heavy-ion collisions at lower energies of $\sqrt{s_{NN}} = 4$-11 GeV, which would deliver similar multiplicities to the mid-central collisions at RHIC and the LHC. At these and lower multiplicities significant modifications of the resonance properties due to the formation of the dense and relatively long-lived hadronic phase have been revealed [5]. This makes a study of short-lived resonances an important task for future experiments at NICA since observation of modifications of the resonance properties can shed light on the properties and dynamics of the system produced in heavy-ion collisions. Proper understanding and description of the system evolution in models, especially at later stages of the collisions is vital for correct and unambiguous interpretation of many physical observables such as particle flow, integrated and differential yields, and correlations.
2. Expected properties of the short-lived resonances at NICA energies

Due to the lack of experimental data, the properties of the resonances were studied using the general-purpose event generators such as UrQMD [6], PHSD [7], and AMPT [8], which include simulation of the late hadronic interactions. Yields of the resonances at midrapidity (|y| < 1) in Au+Au collisions were extracted from the invariant mass distributions of daughter particles survived to the final state corrected for the branching ratios. The following decay channels were used for reconstruction of the resonances: \( r(770)^0 \rightarrow \pi^+\pi^-\), \( K^+(892)^0 \rightarrow \pi^+K^0\), \( K^+(892)^+ \rightarrow \pi^+K^0\), \( \Lambda(1520) \rightarrow pK^+\), \( \Sigma(1385)^+ \rightarrow \pi^+\Lambda\), and \( \Xi(1530)^0 \rightarrow \pi^+\Xi^-\). The procedure has much in common with the reconstruction of resonances in real data analysis except for 100% reconstruction and identification efficiency of the final state particles. The resonance yields were extracted as a function of the particle momentum and the final state charged-particle multiplicity.

The extracted ratios of the resonance yields (\( p_T \)-integrated) to the yields of long-lived particles with similar quark contents such as \( r(770)^0/\pi\), \( K^+(892)/K\), \( \phi(1020)/K\), and \( \Lambda(1520)/\Lambda\) have been published in [9, 10]. The \( \Sigma(1385)^0/\Lambda\) and \( \Xi(1530)^0/\Xi\) ratios estimated using UrQMD and PHSD event generators as a function of the final-state charged-particle multiplicity are shown in Figure 1. Production of short-lived \( r(770)^0\), \( K^+(892)\), and \( \Sigma(1385)^0\) resonances is predicted to be suppressed in central Au+Au collisions at \( \sqrt{s_{NN}} = 4.11\) GeV compared to peripheral collisions. Predictions for the long-lived \( \phi(1020)\) meson are model dependent: the UrQMD and PHSD predict a suppressed production of the meson while AMPT predicts an enhancement at \( \sqrt{s_{NN}} = 4.11\) GeV [9, 10]. Production of \( \Xi(1530)^0\) with an intermediate lifetime is predicted to be suppressed by PHSD at all collision energies. Predictions of UrQMD are collision-energy dependent, production of the resonance is suppressed only at \( \sqrt{s_{NN}} > 7.7\) GeV. The predicted modification of the resonance yields do not depend on the collision energy and are defined by the final state multiplicity except for \( \Xi(1530)^0\) in UrQMD.

Figure 2 shows double ratios \( \Sigma(1385)^0/\Lambda\) and \( \Xi(1530)^0/\Xi\) as measured in central and peripheral collisions estimated as a function of transverse momentum. One can see that the observed resonance yield modifications occur at low momentum, all ratios converge to unity at higher momentum. The predicted modifications and their dependence on the final state multiplicity and transverse momentum are qualitatively similar to those observed for resonances in heavy-ion collisions at RHIC and the LHC [5]. In the latter case, the observed modifications were assigned to rescattering and regeneration processes occurring in the late hadronic phase. The obtained results hint at the importance of the hadronic phase effects at lower collision energies expected at NICA. The hadronic phase effects should be taken into account when the experimental results are interpreted and compared to model calculations. At the same time, the resonances will serve as a unique tool to tune and verify the hadronic phase models and the corresponding assumptions.

Another interesting observable is the reconstructed line shape of the resonances. Due to rescattering and regeneration occurring in the hadronic phase, the reconstructed mass peaks of resonances do not necessarily coincide with the vacuum shapes. The effect of the hadronic phase depends on the daughter particle rescattering cross-sections, lifetimes of the resonance and the hadronic phase. The most prominent mass modifications are expected in central heavy-ion collisions at low momentum when the parent resonance and the daughter particles spend most of the time in the dense hadronic medium. Figure 3 shows the UrQMD predictions for the masses of the \( r(770)^0\) and \( \phi(1020)\) mesons reconstructed at low (\(< 0.5\) GeV/c) and high (\(> 2\) GeV/c) momenta in central, semicentral and peripheral Au+Au collisions at \( \sqrt{s_{NN}} = 11\) GeV. These particles present two extreme cases of resonances with very short (~ 1 fm/c) or very long (~ 45 fm/c) lifetimes. At high momentum, the reconstructed peak shapes of the resonances are consistent with a vacuum shape at all centralities. At low momentum, the reconstructed peak shapes show a clear centrality dependence. In the case of short-lived \( r(770)^0\) meson the reconstructed peak shape is significantly distorted in the final state. The distortion is most prominent in the central collisions but is also present in peripheral ones. For the long-lived \( \phi(1020)\) meson, the mass modifications are also present in central heavy-ion collisions but they are rather modest. The effect of the predicted mass modifications for the resonances is twofold. First, the mass modifications carry information about the
medium properties, lifetime and density of the hadronic phase, which is a subject of interest. Second, the mass modifications influence the resonance yield measurements using the invariant mass method. In most analyses, the resonance peaks in the invariant mass distributions are fit to a combination of a polynomial for the remaining correlated background and the vacuum peak-shape for the signal. In this approach, the peak modifications such as the tails enhancement (see Figure 3(a)) will not be seen and accounted for in the peak model. On the contrary, it will be subtracted by the polynomial and the extracted resonance yield will not account for it. This effect should obviously be considered when results of the measurements are interpreted or compared to measurements in leptonic decay channels.

Figure 1. $p_T$-integrated $\Sigma(1385)/\Lambda$ (a,b) and $\Xi(1530)/\Xi$ (c,d) ratios estimated using UrQMD (left) and PHSD (right) event generators as a function of the final-state charged-particle multiplicity in Au+Au collisions at $\sqrt{s_{NN}} = 4, 7.7, 9$ and $11$ GeV.

3. Reconstruction of resonances in the MPD detector at NICA
The UrQMD was used to simulate Au+Au collisions at different energies, $\sqrt{s_{NN}} = 4, 7.7$ and $11$ GeV. All simulated particles have been tracked through the detector materials using Geant4. Simulation of the realistic response of each of the MPD detector subsystems, reconstruction of tracks and signals have been performed within the ‘mpdroot’ framework. The following basic track selection cuts were used: tracks with a rapidity cut of $|\eta| < 1.0$ have at least 24 hits in the TPC out of 54 maximum possible, primary particles are matched to the primary vertex within 3$\sigma$, transverse momentum $p_T > 50$ MeV/$c$, final state particles are identified using dE/dx measurements in the TPC and the time-of-flight measurements in the TOF. For the reconstruction of weakly decaying daughter particles such as $K_S^0$ and $\Lambda$, a set of topology cuts for the reconstruction of secondary vertices was used. In total, $10^7$ events were simulated at $\sqrt{s_{NN}} = 11$ GeV and $5 \times 10^6$ events at $\sqrt{s_{NN}} = 4$ and $7.7$ GeV.
Figure 2. $p_T$-differential $\Sigma(1385)^+/\Lambda$ (a,b) and $\Xi(1530)^0/\Xi$ (c,d) ratios estimated using UrQMD (left) and PHSD (right) event generators in Au+Au collisions at $\sqrt{s_{NN}} = 4, 7.7, 9$ and 11 GeV.

Figure 3. Reconstructed masses of $\rho(770)^0$ (a,b) and $\phi(1020)$ (c,d) resonances at low (left) and high (right) momenta in Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV (UrQMD predictions).
Details of the $\rho(770)^0$, $K^*(892)$, $\phi(1020)$, and $\Lambda(1520)$ reconstruction have been published in [5-8]. Figure 4 shows the reconstruction efficiencies estimated for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ resonances at midrapidity as a function of transverse momentum in Au+Au collisions at different energies. The lower reconstruction efficiency for $\Xi(1530)^0$ is explained by the necessity to reconstruct decays of intermediate $\Xi^0$ baryons in addition to the reconstruction of $\Lambda$. The efficiencies show a modest multiplicity dependence responsible for the variation of efficiencies with the collision energy.

![Figure 4. $p_T$-dependent reconstruction efficiencies evaluated for $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b) resonances in Au+Au collisions at $\sqrt{s_{NN}} = 4$, 7.7 and 11 GeV.](image)

The resonance raw yields are extracted from the invariant mass distributions accumulated for pairs of daughter particles reconstructed in the final state. After correcting for the branching ratios and the reconstruction efficiencies, the yields are compared to truly generated ones in Figure 5 for the whole set of resonances under study. One can see that the reconstructed resonance yields are in agreement with the truly generated ones that validate the developed reconstruction procedures. An important conclusion from Figure 5 is that reconstruction of resonances is going to be possible starting from very low momenta except for $\phi(1020)$ and $\Xi(1530)^0$. This is one of the main features of the MPD detector since resonance measurements at low momentum are expected to be most sensitive to processes occurring at different stages of heavy-ion collisions. At high momentum, the range of measurements is limited by the size of the accumulated data sample. The figure demonstrates the MPD capabilities for the reconstruction of resonances in Au+Au collisions at different energies using an accumulated data sample of $\sim 10^7$ events. However, a detailed study of resonances as a function of transverse momentum and collision centrality would need $\sim 10^8$ events for $\rho(770)^0$, $K^*(892)$, $\phi(1020)$, $\Lambda(1520)$ and $\Sigma(1385)^\pm$ and up to $10^9$ events for $\Xi(1530)^0$, which needs reconstruction of weak decays of $\Lambda$ and $\Xi$.

4. Summary and Conclusions

The general-purpose event generators predict high sensitivity of the short-lived resonances to properties of the late hadronic phase in heavy-ion collisions at NICA energies. Significant modifications of the reconstructed resonance line shapes and yields are expected in central heavy-ion collisions at low transverse momentum. Feasibility studies demonstrate good capabilities of the MPD detector for the reconstruction of $\rho(770)^0$, $K^*(892)^{\pm,0}$, $\phi(1020)$, $\Lambda(1520)$, $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ resonances in heavy-ion collisions in a wide transverse momentum range. The first-look results for resonances may become available with a data sample of $10^7$ Au+Au events.
Figure 5. Transverse momentum spectra reconstructed in Au+Au collisions at $\sqrt{s_{NN}} = 4, 7.7$ and 11 GeV compared to truly generated spectra shown with solid lines of the same color for $\rho(770)^0$ (a), $K^*(892)^0$ (b), $\phi(1020)$ (c), $\Lambda(1520)$ (d), $\Sigma(1385)^\pm$ (e) and $\Xi(1530)^0$ (f) resonances.

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