Measurement of short-lived $\phi(1020)$ and $K^*(892)^0$ resonances in heavy-ion collisions at NICA energies using the MPD experiment

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Abstract. The $K^*(892)^0$ and $\phi(1020)$ mesons are copiously produced in hadronic and heavy-ion collisions and carry a wealth of information on different aspects of the interactions, including the properties of the hadronic phase, relative interplay of the radial flow and coalescence at intermediate momentum. For these reasons, measurements of $K^*(892)^0$ and $\phi(1020)$ production is an important part of the experimental program of the MPD experiment at NICA. We discuss prospects for $K^*(892)^0$ and $\phi(1020)$ measurements in the MPD experimental setup as well as results of the feasibility studies performed using the full-scale Monte Carlo simulations of the detector response.

1. Introduction

Resonances are excited hadronic states, which have different masses and quark contents, lifetimes and strangeness. This makes these particles very useful in the study of reaction dynamics and particle production mechanisms. Due to their short lifetimes, resonances serve as a unique tool to study properties of the late hadronic phase, which is an inherent part of heavy-ion collisions. Reconstructed resonance yields are defined by the resonance yields at chemical freeze-out. Then hadron rescattering and regeneration are expected to occur between chemical and kinetic freeze-out. As a result, one loses the signal and observes suppressed resonance yields. However, there is an opposite process of regeneration when the pseudo-elastic scattering of background hadrons may result in a production of resonances thus increasing the measured yields. For most of the cases, it is expected that rescattering takes over regeneration and cumulative effect of the hadronic phase is a loss of signal. The cumulative effect of processes occurring in the hadronic phase obviously depends on the lifetime of the resonance and lifetime of the hadronic phase, hadron density and type of the daughter particles. For example, rescattering cross sections for strange daughter particles with surrounding hadrons changes kinematics of the decays and resonances can no longer be reconstructed. As a result, one loses the signal and observes suppressed resonance yields. However, there is an opposite process of regeneration when the pseudo-elastic scattering of background hadrons may result in a production of resonances thus increasing the measured yields. For most of the cases, it is expected that rescattering takes over regeneration and cumulative effect of the hadronic phase is a loss of signal. The cumulative effect of processes occurring in the hadronic phase obviously depends on the lifetime of the resonance and lifetime of the hadronic phase, hadron density and type of the daughter particles. For example, rescattering cross sections for strange daughter particles are expected to be smaller than that for light hadrons containing only $u$ and $d$-quarks. Theoretical models and event generators predict that the line-shape and yield modifications are most prominent at low transverse momenta because resonances should spend as much time in the medium as possible to be affected. Hadronic phase is present in any heavy-ion collisions and for most of the cases, it significantly affects...
the measured observables. Without a proper understanding of the hadronic phase interpretation of experimental results is problematic.

Properties of the resonances were studied in hadronic decay channels by NA49 at SPS (CERN, Switzerland), STAR/PHENIX at RHIC (BNL, USA) and ALICE at LHC (CERN, Switzerland). Measurements are available for $\rho(770)$, $K'(892)^0$, $\Lambda(1520)$, $\Xi(1530)^0$ and $\phi(1020)$ mesons, which cover a wide range of lifetimes from 1.3 fm/c for $\rho(770)$ up to 46.2 fm/c for $\phi(1020)$ mesons [1]. Figure 1 shows ratios of the resonance yields to yields of quasi-stable particles having similar quark content measured at RHIC and LHC. Ratios $\rho(770)^0/\pi$, $K'(892)^0/K$, $\Sigma(1385)^0/\Lambda$, $\Lambda(1520)/\Lambda$, $\Xi(1530)^0/\Xi$ and $\phi(1020)/K$ are shown as a function of multiplicity in $p+p$, $p+A$ и $A+A$ collisions [2-4]. One can see that the ratios have a very weak dependence on collision energy and are mostly defined by event multiplicity rather than by the size of colliding nuclei. The particle ratios are suppressed in central collisions of heavy ions for particles with small lifetimes, $\tau < 20$ fm/c, compared to $p+p$ and peripheral $A+A$ collisions. For longer-lived resonances, the ratios do not show any significant modifications. The longest-lived resonance - $\phi(1020)$ meson behaves as a quasi-stable particle. These results suggest an existence of the dense hadronic phase that lives long enough to cause significant suppression of the short-lived resonances production. It is also interesting to note that the measured ratios are well described by the EPOS3 event generator, which uses UrQMD to describe the hadronic cascades [5,6]. The measurements also allowed estimation of the hadronic phase lifetime to be $\tau_{had} > 2$ fm/c [7].

![Figure 1](ALICE Preliminary)

Figure 1. $\rho(770)^0/\pi$, $K'(892)^0/K$, $\Sigma(1385)^0/\Lambda$, $\Lambda(1520)/\Lambda$, $\Xi(1530)^0/\Xi$ and $\phi(1020)/K$ ratios as a function of multiplicity in $p+p$, $p-Pb$, Xe-Xe, and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76-7$ TeV and in $p$ and $Au-Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, with a comparison to EPOS3.

A similar study of resonance production is of great importance for the heavy-ion program at NICA (Dubna, Russia). The MPD experiment at NICA will study the hot and dense medium produced in heavy-ion collisions at the energies of $\sqrt{s_{NN}} = 4-11$ GeV. Any signatures of the critical point or phase transition, which are subjects of greatest interest at NICA, will be smeared in the late hadronic phase. This is why a proper understanding of the properties of the hadronic phase is vital for correct interpretation of the measured signals.

In this contribution, we discuss expected properties of $K'(892)^0$ and $\phi(1020)$ mesons reconstructed in hadronic decay channels in Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV. We also present prospects for experimental measurement of these resonances using the MPD detector.
2. Properties of $K'(892)^0$ and $\phi(1020)$ mesons in the late hadronic phase

In this work, the UrQMD v.3.4 event generator [6] was used to estimate influence of the hadronic phase on the reconstructed properties of $K'(892)^0$ and $\phi(1020)$ mesons. The UrQMD used as an afterburner for EPOS3 [5] proved to be very successful in description of resonance properties in heavy-ion collisions at $\sqrt{s_{NN}} = 200$-5000 GeV (see Figure 1). The Au+Au collisions were simulated at the top energy of the NICA collider, $\sqrt{s_{NN}} = 11$ GeV. The UrQMD provides the means to trace the full history of each particle produced in the final state, including rescattering and regeneration processes. In order to estimate influence of the hadronic phase, the particle differential production spectra were accumulated taking into account different production mechanisms. The first type of spectra (denominator) was accumulated by accepting all $K'(892)^0$ and $\phi(1020)$ mesons directly produced in the event or originating from decays of heavier hadrons. The second type of spectra (numerator) did not include the particles whose mass could not be reconstructed in the final state because at least one of the daughter hadrons was either absorbed in regeneration process or experienced a re-scattering resulting in a reconstructed mass of the mother particle lying far away from the expected one. This spectrum also included resonances produced in regeneration of the background hadrons ($\pi K \rightarrow K'$ or $KK \rightarrow \phi$). Ratios of numerators and denominators are shown in Figure 2, where red distributions correspond to peripheral collisions with impact parameter larger than 10 fm and black distributions correspond to most central collisions with impact parameter smaller than 5 fm. In the case of central collisions, one observes a significant suppression of $K'(892)^0$ meson production at low transverse momentum due to loss of daughter particles in hadron rescattering. At intermediate momentum, one observes a modest enhancement of $K'(892)^0$ production due to a regeneration of background hadrons. In case of peripheral collisions, one can also observe a suppression at low momentum, however, it is much less prominent. At intermediate transverse momentum no modifications are observed within uncertainties. For $\phi(1020)$ meson one observes a small suppression of the particle yield at low momentum in central Au+Au collisions and modest enhancement at intermediate momentum. In peripheral collisions production of $\phi(1020)$ mesons is not modified. Much smaller effects for $\phi(1020)$ meson compared to that for $K'(892)^0$ can be explained by the difference of the lifetimes, 46.2 fm/c for $\phi(1020)$ versus 4.6 fm/c for $K'(892)^0$.

![Figure 2](image)

**Figure 2.** Ratios of $K'(892)^0$ (a) and $\phi(1020)$ (b) yields in central (black) and peripheral (red) Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV as predicted by UrQMD event generator. Numerator in ratio didn’t include the particles whose mass could not be reconstructed in the final state due to influence of the hadronic phase, while denominator in ratio accepted all $K'(892)^0$ and $\phi(1020)$ mesons directly produced in the event or originating from decays of heavier hadrons.

Surprisingly, predictions of UrQMD event generator for Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV are consistent with experimental observations shown in Figure 1 for heavy-ion collisions at much higher energies, $\sqrt{s_{NN}} > 200$ GeV. Only experimental study of resonance production at NICA energies can provide the means to test different model predictions.
3. Reconstruction of $K^*(892)^0$ and $\phi(1020)$ mesons in the MPD experimental setup

The $K^*(892)^0$ and $\phi(1020)$ are reconstructed in the hadronic decay channels, $K^* \rightarrow K\pi$ and $\phi \rightarrow KK$, where symbols $K^*$ and $\phi$ stand for a sum of particles and anti-particles. The considered decay modes have large branching ratios and only charged particles in the final state that significantly simplifies measurement and identification of daughter particles. Description of the MPD detector can be found elsewhere [8]. The large Time Projection Chamber (TPC) is used for charged track reconstruction and momentum measurements with a typical resolution of $\Delta p/p \sim 2\%$. Measurements of particle ionization losses (dE/dx) in the TPC with a resolution of 6-8\% and time of flight in the TOF subsystem with a resolution of 60-100 ps are used for hadron identification.

The minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV were simulated with UrQMD [6]. A sample of particles generated by UrQMD for each event was used as input data for simulation of the detector response. Description of the detector materials and particle tracking was modeled by using the ‘mpdroot’, which is an official software of the MPD Collaboration based on Geant (v.3 or v.4). The output data contained tables of reconstructed tracks and information about their association with signals in different subsystems. The obtained tables were used to accumulate the invariant mass distributions for each of the particles of interest. The presented study is based on the analysis of half a million events.

Simulated distribution of the primary vertex $z$-coordinate followed a Gaussian distribution with a width of $\sim 23$ cm, which corresponds to expected geometry of the beam crossing in the NICA collider. Only events with $z$-coordinate of the vertex within $\pm 50$ cm from a geometrical center of the detector were accepted in the analysis. The charged particle tracks were required to be reconstructed in the TPC and have at least 39 measured points out of 54 maximum possible. Tracks are required to be reconstructed in the central part of the detector and have a pseudo-rapidity in the range $|\eta| < 1.0$. The tracks were required to be matched to the primary vertex within $2\sigma_{x,y,z}$, where $\sigma_{x,y,z}$ is a momentum dependent spatial resolution of the vertex measurements in three different projections. The minimum momentum of particles was required to be $p_T > 50$ MeV/c. The charged particles were counted as identified if their combined probabilities to be identified as pions and kaons in the TPC and TOF exceeded 75\%.

Figure 3 shows invariant mass distributions obtained for $\pi K$ and KK pairs of the opposite sign after all selections. One can hardly see any signals from the resonance decays on top of the huge combinatorial background. In order to estimate the uncorrelated combinatorial background, a mixed event invariant mass distributions were also calculated. These distributions were obtained by taking a particle of one sign from a current event and the opposite sign particle from a different event with a similar topology. It was required that maximum difference in $z$-coordinate of the event vertex and multiplicity between the mixed events did not exceed 5 cm and 10 particles, respectively. Each event was mixed with ten other events. The obtained mixed event invariant mass distribution was scaled to the same event invariant mass distribution in the limited mass range close to the expected resonance mass.

Figure 4 shows examples of the invariant mass distributions after subtraction of the scaled mixed event background. After subtraction, one can see peaks corresponding to the resonance decays sitting on top of the remaining background. Resulting distributions were fit to a combination of a polynomial to describe the background and a Voigtian function (a convolution of Breit-Wigner and Gaussian functions) to describe the signal. The width ($\Gamma$) of the resonances was fixed to the PDG values [1]. The extracted values of yields, mass and mass resolution are shown in the figures. The values of the mass resolution are much smaller compared to the natural width of $K^*(892)^0$ resonance, $\Gamma \sim 50$ MeV/c$^2$. Thus the $K^*(892)^0$ peak is reconstructed close to its natural shape. However, the same value of the mass resolution is comparable to the natural width of $\phi(1020)$ meson, $\Gamma \sim 4.5$ MeV/c$^2$. It results in a significant smearing of the natural shape of the $\phi(1020)$ meson making it look more like a Gaussian.
Figure 3. Invariant mass distributions for $\pi K$ (a) and $KK$ (b) pairs of opposite sign. Black distributions correspond to pairs in the same event. Red distributions are for pairs taken from different events (mixed events).

Figure 4. Invariant mass spectra for $\pi K$ (a) and $KK$ (b) pairs of opposite sign after subtraction of the scaled mixed event background. The distributions are fit to a combination of polynomial and Voigtian function to account for the remaining background and signal peaks.

Figure 5 shows reconstruction efficiencies for $K^*(892)^0$ and $\phi(1020)$ mesons which account as for detector acceptance as for loss of efficiency due to detector effects and selection cuts. The efficiencies rapidly increase with transverse momentum and saturate at intermediate transverse momentum.
Figure 5. Reconstruction efficiencies for K*(892)\(^0\) (a) and \(\phi\) (1020) (b) mesons as a function of particle transverse momentum.

The obtained results show that properties of K*(892)\(^0\) and \(\phi\) (1020) mesons can be experimentally studied in Au+Au collisions at \(\sqrt{s_{NN}} = 11\) GeV by using the MPD detector. This particles can be measured at very low transverse momenta, \(p_T < 1\)–2 GeV/c, where effects of the hadronic phase are expected to be most significant. The higher \(p_T\) reach of the measurements will be limited only by available statistics. For a comprehensive study of K*(892)\(^0\) and \(\phi\) (1020) mesons one would need to accumulate \(\sim 10^7\) minimum bias Au+Au collisions that is within the reach of the MPD physical program for year one.

Acknowledgements
This work was funded by RFBR according to the research project № 18-02-40038 and partially supported by the National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013). The presented results were obtained using the resources of the PIK Data Center of the NRC «Kurchatov Institute» - PNPI.

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