Production and reconstruction of short-lived $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and $\Lambda(1520)$ resonances as a function of centrality and energy in Au+Au collisions at NICA

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Abstract. The short-lived resonances have proved to be very useful in the study of heavy-ion collisions at SPS, RHIC, and the LHC. Properties of these particles measured in dominant hadronic decay channels carry a wealth of information about the hadron chemistry and reaction dynamics. Resonances containing one or two strange quarks contribute to the study of the strangeness enhancement phenomenon predicted as a signature of the phase transition to quark-gluon plasma in heavy-ion collisions. Resonance integrated and differential yields are sensitive to the hadron re-scattering and regeneration in the hadronic phase. The resonance production has only scarcely been studied in heavy-ion collisions at NICA energies. These proceedings are devoted to the review of the expected properties of the resonances and their sensitivity to different stages of Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV. Results of feasibility studies for reconstruction of $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and $\Lambda(1520)$ resonances in the MPD experimental setup as a function of collision energy and centrality are presented.

1. Introduction

Relativistic heavy-ion collisions allow studying the properties of QCD matter at high temperatures and densities. The system formed in such collisions evolves and passes through different stages, from the early stage of deconfinement to the late stage of the hadron gas. Measurements of short-lived hadronic resonances allow studying the properties of the medium at various stages of its evolution. Due to short lifetimes, a significant part of the resonances decays inside the evolving system. Measurement of the masses and widths of resonances is a tool to determine their properties in the medium. For instance, some theoretical models predict changes in the mass and width of resonances as a result of the chiral symmetry restoration. Re-scattering of daughter particles and hadron recombination can change the differential yields and spectral characteristics of resonances measured in hadronic decay channels. Resonances with different quark content can also help to better understand the mechanisms responsible for strangeness enhancement in nuclear collisions. Moreover, resonances make an important contribution to the systematic study of the excess yield of baryons in the intermediate transverse momentum $p_T$ region and the dependence of parton energy loss on its type at high $p_T$. 
Future NICA collider in Dubna will study heavy-ion collisions at nucleon-nucleon collision energies in the centre-of-mass system of \( \sqrt{s_{NN}} = 4-11 \) GeV. The systematic study of the properties of short-lived resonances in nuclear collisions in this energy region has only scarcely been carried out before both experimentally and theoretically [1–4]. However, similar studies were carried out at significantly higher interaction energies in NA49 experiments [5] at the SPS accelerator (CERN, Switzerland), PHENIX [6] and STAR [7] at the RHIC collider (BNL, USA) and in the ALICE experiment [8] at the LHC collider (CERN, Switzerland). Despite the large difference in the energy of nuclear collisions (\( \sqrt{s_{NN}} = 20-5000 \) GeV), all experiments showed qualitatively similar results. Properties of short-lived resonances measured in these experiments turned out to be very sensitive to the properties of the medium formed in nuclear collisions.

Yields of short-lived resonances such as \( \rho(770)^0 \) [9], \( K^*(892)^0 \) [8] and \( \Lambda(1520) \) [10] were found to be suppressed by 20–50% in central heavy-ion collisions. Measurements for longer-lived resonances such as \( \phi(1020) \) [6] did not reveal similar behaviour. Suppression observed for \( \rho(770)^0 \), \( K^*(892)^0 \) and \( \Lambda(1520) \) was explained by the re-scattering of daughter particles in a dense hadronic medium after chemical freeze-out, followed by the loss of daughter particles due to inelastic interactions or by smearing out the angular correlations between daughter particles due to elastic interactions. The longer the daughter particles are in the hadronic medium, the greater is the role of re-scattering. Therefore, the magnitude of suppression depends on the lifetime of the resonance itself as well as the lifetime and density of the hadron phase of the heavy-ion collisions. Hadron phase lifetime (\( \sim 10 \) fm/c) and its properties estimated with the resonance measurements are important in order to test and tune the theoretical models and event generators [11–13].

The high energy experiments listed above did not observe any significant modifications in the shape of the reconstructed resonance signals in the hadron decay channels, which might indicate either insufficient sensitivity of the measurements or negligible influence of the expected chiral symmetry restoration and hadron re-scattering on the reconstructed signal shapes [6,8]. Nevertheless, a change in the shape of the \( \rho(770)^0 \) meson signal was seen in dilepton decay channels in heavy-ion collisions at SPS [14] and RHIC [15]. Lepton and hadron decay channels of the \( \rho \)-meson might have different sensitivity to different stages of heavy-ion collisions. For example, \( \pi^+ \pi^- \) pairs from \( \rho \)-mesons that decay at the stage of chiral symmetry restoration could be lost due to the re-scattering and \( \rho \)-mesons measured in the final state are mostly formed by recombination of charged pions in a hadron gas. The absence of significant modifications for the spectral properties of resonances measured in hadron decay channels is a separate interesting experimental result that requires theoretical description.

2. Properties of \( \rho(770)^0 \), \( K^*(892)^0 \), \( \phi(1020) \) and \( \Lambda(1520) \) resonances in the hadronic phase

In the absence of experimental data at NICA energies, only the event generators can be used to estimate resonance yields and background levels. UrQMD[11], AMPT[12] and PHSD[13] event generators were used to simulate Au+Au collisions at \( \sqrt{s_{NN}} = 11 \) GeV. Resonances with different lifetimes (from \( \rho(770)^0 \)-meson with a lifetime of \( \sim 1 \) fm/c up to \( \phi(1020) \)-meson with a lifetime of \( \sim 46 \) fm/c) were studied. Due to different lifetimes, the resonances decay at different stages of the system evolution and have different sensitivity to the effects of re-scattering and recombination in the hadron gas.

Figure 1 shows ratios of integrated yields of resonances to the yields of stable particles with similar quark contents scaled to unity in peripheral Au+Au collisions versus charged particle multiplicity dN/dη at mid-rapidity \( |\eta|<1 \). The shortest-lived \( \rho(770)^0 \) and \( K^*(892)^0 \) resonances (Fig.1a and Fig.1b) are strongly suppressed in central Au+Au collisions at the energy of \( \sqrt{s_{NN}} = 11 \) GeV when compared to peripheral collisions. The suppression is explained by the loss of the measured signal as a result of re-scattering of daughter particles (in this case, charged \( \pi \) and K-mesons) in the hadronic phase of heavy-ion collisions. Predictions for the longer-lived \( \phi(1020) \)-meson seem to be model dependent (Fig.1c). UrQMD and PHSD predict moderate excess of resonance yield in central Au+Au collisions as a result of K-meson recombination prevailing over re-scattering. At the same time, AMPT generator predicts suppression of \( \phi(1020) \)-meson yields. Yields of \( \Lambda(1520) \) baryon can only be predicted with UrQMD (Fig.1d) which shows enhanced yields of this resonance in central Au+Au collisions (Fig.1d). The
hadron phase of heavy-ion collisions has an opposite effect on the yields of resonances having short (less than 5 fm/c) or relatively long (more than 10 fm/c) lifetimes.

![Graphs showing ratios of integrated yields of resonances](image)

Figure 1. Ratios of integrated yields of resonances (a) $\rho(770)^0$, (b) $K^*(892)^0$, (c) $\phi(1020)$ and (d) $\Lambda(1520)$ to the yields of quasi-stable particles with similar quark contents scaled to unity in peripheral collisions versus charged particle multiplicity $dN_c/d\eta$ obtained with UrQMD, PHSD and AMPT event generators for Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV at mid-rapidity $|\eta|<1$.

3. Reconstruction of $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and $\Lambda(1520)$ resonances in the MPD

The capability of resonance measurements using the MPD experimental setup at NICA was studied in the following way. UrQMD event generator was used to simulate $10^7$ Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV and $5 \cdot 10^5$ Au+Au collisions at $\sqrt{s_{NN}} = 4$ GeV. The Geant-based MpdRoot software package was used to simulate the passage of particles through the detector materials and simulate the response of different detector subsystems. The MpdRoot package is an official software of the MPD Collaboration, which keeps up the latest versions of the detector geometry, construction materials and subsystem performance. Then MpdRoot tracked particles produced by UrQMD as well as their decay products through the MPD experimental setup and generated detector signals down to the level of individual electronic channels.
Figure 2 shows estimated reconstruction efficiencies ($A\times\varepsilon$) for $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and $\Lambda(1520)$ resonances in the MPD versus transverse momentum $p_T$ of the particle for most central (0-20%), semi-central (20-40%, 40-60%) and peripheral (60-80%, 80-100%) Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV. The largest efficiency at low $p_T$ is observed for $\rho(770)^0$-meson (Fig. 2a). Efficiencies for $K^*(892)^0$ (Fig. 2b) and $\Lambda(1520)$ (Fig. 2d) increase with $p_T$ and reach a maximum at 40-60%. For the $\phi$-meson (Fig. 2c), small efficiency at low $p_T$ can be explained by a small difference in masses of $\phi$-meson and two kaons in the final state. Value of ($A\times\varepsilon$) increases with $p_T$ and reaches 40-50% at high $p_T$. For all considered resonances, the efficiencies show a clear centrality dependence, which is explained by multiplicity dependent efficiency of track reconstruction in the TPC and primary vertex resolution. High track multiplicity observed in most central Au+Au collisions makes resonance reconstruction more challenging.

**Figure 2.** Values of reconstruction efficiencies ($A\times\varepsilon$) for (a) $\rho(770)^0$, (b) $K^*(892)^0$, (c) $\phi(1020)$ and (d) $\Lambda(1520)$ resonances in the MPD experimental setup versus transverse momentum $p_T$ of the particle. The efficiencies are shown for most central (0-20%), semi-central (20-40%, 40-60%) and peripheral (60-80%, 80-100%) Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV.

Figure 3 shows representative examples of invariant mass distributions for $\pi K$ and $KK$ pairs of opposite charge, which were used to extract the $K^*(892)^0$ and $\phi(1020)$ resonance yields. The invariant mass distributions are presented for a given $p_T$ interval from 0.6 to 0.8 GeV/c. The combinatorial background was estimated using the mixed event technique: each event was combined with other 10 events that have similar topology ($z$-vertex of the primary vertex and event multiplicity). The estimated background was then subtracted from the invariant mass distributions. Prominent signals from the decay of the resonances are seen after the subtraction. To extract the resonance yields, the distributions are fit to a combination of Voightian and polynomial functions for signal and the remaining background, respectively. A clear collision energy dependence of signal-to-background ratio can be observed when
invariant mass distributions obtained for $\sqrt{s_{NN}} = 11$ GeV and $\sqrt{s_{NN}} = 4$ GeV are compared. The better signal-to-background ratio at lower collision energy is explained by lower charged-particle multiplicity and smaller combinatorial background.

Figure 3. Invariant mass distributions with signals corresponding to decays of (a, b) $K^*(892)^0$ and (c, d) $\phi(1020)$ resonances for Au+Au collisions at $\sqrt{s_{NN}} = 4$ GeV (a, c) and $\sqrt{s_{NN}} = 11$ GeV (b, d).

Figure 4 presents results of a so-called closure test for the reconstruction of $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and $\Lambda(1520)$ resonances in Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV. Red histograms correspond to the initially generated resonance $p_T$ spectra. Black dots show reconstructed resonance $p_T$ spectra obtained by extracting the resonance yields from the invariant mass distributions and correcting them for the reconstruction efficiencies. As one can see, initially generated and reconstructed resonance $p_T$ spectra are in good agreement with each other within statistical uncertainties that justifies the developed reconstruction procedure.

Results on resonance production presented in these proceedings contribute to the study of the properties of the medium formed in heavy-ion collisions and show the possibility of studying the resonances in nuclear interactions at NICA energies using the MPD experimental setup. The MPD detector will allow measuring the yields of $\rho(770)^0$, $K^*(892)^0$, $\phi(1020)$ and (d) $\Lambda(1520)$ already during the first year of NICA data taking.
Figure 4. Generated (red) and reconstructed (black) \( p_T \) spectra of (a) \( \rho(770)^0 \), (b) \( K^*(892)^0 \), (c) \( \phi(1020) \) and (d) \( \Lambda(1520) \) resonances in Au+Au collisions at \( \sqrt{s_{NN}} = 11 \) GeV.

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References
[1] Kumar L et al. 2015 EPJ Web of Conferences 97 00017
[2] Adamczyk L et al. 2013 Phys. Rev. Lett. 110 0142301
[3] Adamczyk L et al. 2013 Phys. Rev. C 88 014902
[4] Adamczyk L et al. 2016 Phys. Rev. C 93 014907
[5] Afanasiev S et al. 2000 Phys. Lett. B 491 59–66
[6] Adare A et al. 2011 Phys. Rev. C 83 024909
[7] Abelev B et al. 2007 Phys. Rev. Lett. 99 112301
[8] Abelev B et al. 2015 Phys. Rev. C 91 024609
[9] Acharya S et al. 2015 Phys. Rev. C 99 064901
[10] Acharya S et al. 2019 Phys. Rev. C 99 024905
[11] Knospe A et al. 2016 Phys. Rev. C 93 014911
[12] Lin Z et al. 2015 Phys. Rev. C 72 064901
[13] Ehehalt W and Cassing W 1996 Nucl. Phys. A 602 449
[14] Arnaldi A et al. 2006 Phys. Rev. Lett. 96 162302
[15] Adare A et al. 2011 Phys. Rev. C 93 014904