Resonance production and interaction from low to high energy

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Abstract.
Measurements of short-lived hadronic resonances are used to probe the properties of the hadronic phase in ultra-relativistic heavy-ion collisions. Since these resonances have lifetimes comparable to that of the produced fireball, they are sensitive to the competitive re-scattering and regeneration effects in the hadronic gas, which modifies the observed particle momentum distributions and yields after hadronization. With different masses, quantum numbers, and quark content, hadronic resonances can provide insight into processes that determine the shapes of particle momentum spectra, strangeness production, and the possible onset of collective effects. The system size and collision-energy dependence of resonance production will be presented.

1 Introduction

Hadronic resonances with various lifetimes are valuable probes to study the properties of the hadronic medium formed in ultra-relativistic heavy-ion collisions since the yield ratios of resonances to stable hadrons provide information about the re-scattering and regeneration effects in the hadronic medium. If the loss of resonances due to elastic or pseudo-elastic scattering of their decay products (re-scattering) is dominant over regeneration, the resonance yield after kinetic freeze-out will be smaller than the one originally produced at the chemical freeze-out. Based on the expected lifetime of the hadronic phase (∼ 10 fm/c), the measurement of a comprehensive set of resonances with different lifetimes can be used to study the interplay of particle re-scattering and regeneration. The list of resonances that have been measured is provided in Table 1 with their quark content, decay modes exploited for the measurements, and branching ratios. Studies of resonances play an important role in understanding the strangeness of production. Measurements of strange and non-strange particle yields can be described by grand-canonical thermal models in heavy-ion collisions [1], while canonical suppression is expected in small systems [2]. Enhancement of strangeness production has been observed in high energy nucleus-nucleus (A–A) collisions with respect to pp collisions at RHIC (Relativistic Heavy-Ion Collider) and LHC (Large Hadron Collider) energies [3][4]. The study of strangeness production as a function of the charged particle multiplicity produced in the collision systems from pp to A–A, allows one to investigate the origin of the enhancement.

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Table 1. Lifetime of the measured resonances with their quark content, decay modes exploited for the measurements presented here, and branching ratios \([6]\).

<table>
<thead>
<tr>
<th>(c\tau) (fm)</th>
<th>quark content</th>
<th>Decay modes</th>
<th>BR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho(770)^0)</td>
<td>1.3 ((u\bar{u}+d\bar{d})/\sqrt{2})</td>
<td>(\pi^++\pi^-)</td>
<td>100</td>
</tr>
<tr>
<td>(K^*(892)^0)</td>
<td>4.2 (d\bar{s})</td>
<td>(K^++\pi^-)</td>
<td>66.6</td>
</tr>
<tr>
<td>(\Sigma(1385)^+)</td>
<td>5.5 (uus)</td>
<td>(\Lambda\pi^+ \to (p\pi^-)\pi^+)</td>
<td>87.0</td>
</tr>
<tr>
<td>(\Sigma(1385)^-)</td>
<td>5.0 (dds)</td>
<td>(\Lambda\pi^- \to (p\pi^-)\pi^-)</td>
<td>87.0</td>
</tr>
<tr>
<td>(\Xi(1820)^-)</td>
<td>8.1 (dss)</td>
<td>(\Lambda K \to (p\pi^-)K)</td>
<td>unknown</td>
</tr>
<tr>
<td>(\Lambda(1520))</td>
<td>12.6 (uds)</td>
<td>(p+K^-)</td>
<td>22.5</td>
</tr>
<tr>
<td>(\Xi(1530)^0)</td>
<td>21.7 (uss)</td>
<td>(\Xi^-\pi^+ \to (\Lambda\pi^-)\pi^+ \to ((p\pi^-)\pi^-)\pi^+)</td>
<td>66.7</td>
</tr>
<tr>
<td>(\phi(1020)^0)</td>
<td>44 (s\bar{s})</td>
<td>(K^++K^-)</td>
<td>48.9</td>
</tr>
</tbody>
</table>

Figure 1. The system size dependence of \(\langle K^*(892)^0/K \rangle\) and \(\langle K^*(892)^0/(K^-) \rangle\) yield ratios in p+p, C+C, Si+Si and Pb+Pb collisions at 158 GeV/c (left) and the ratios of \(K^*(892)^0/K\) and \(\phi/K\) as a function of number of charged hadrons for p+p and Au+Au collisions (right).

Besides, the resonance productions are able to contribute to the study of spin alignment in heavy-ion collisions and in-medium energy loss by looking at the nuclear modification factor of resonances. With resonances, one can access to study the chiral symmetry restoration. The calculation from FASTSUM Collaboration [5] shows potential parity doubling of strange resonant states, which could be a signature of chiral symmetry restoration in heavy-ion collisions.

2 Results and discussion

2.1 System size dependence of resonance suppression

The system size dependence of the \(K^*(892)^0/K\) ratio at SPS, RHIC, and LHC energies shows a strong decrease with increasing system size and/or multiplicity density. Figure 1 presents this dependence at the SPS for the NA49 and NA61/SHINE results at 158A GeV/c (left) and
in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (right) [7, 8, 10]. In the Fig. 1, the $\phi/K^*(892)^0$ ratio increases with increasing system size that is different trend with the results of $K^*(892)^0/K$ ratio. It could be due to the re-scattering effect of the $K^*(892)^0$ that has a short lifetime compare to the lifetime of the hadronic phase. The detailed study with models explained in the next paragraph.

The statistical Hadron Resonance Gas Models (HGM) are commonly used to predict particle multiplicities in pp and A–A collisions, using as adjustable parameters the chemical freeze-out temperature $T_{\text{chem}}$, the baryochemical potential $\mu_B$, strangeness saturation parameter $\gamma_s$, etc. The details on different configurations of parameters are provided in Ref. [10]. The ratios between $K^*(892)^0$ yields from NA49 for C+C, Si+Si, and Pb+Pb interactions at 158 GeV/c and the yields predicted by HGM are presented in Figure 2 in the left panel and the yield ratios of data to HGM model for different resonances having different lifetime are shown in the right panel. The yield ratios for $K^*(892)^0$ in pp measurements are close to the HGM prediction, while the ratios decrease by about a factor 2 from C+C and Si+Si reactions to central Pb+Pb collisions. Thus $K^*(892)^0$ yields seem to be strongly affected by interaction in the produced fireball with dominated re-scattering effect. Compared with other resonance particles shown in the right panel in Figure 2, the yield ratio for long-lived resonance might not have an effect on regeneration or re-scattering.

The yield ratios as a function of multiplicity are shown in Figure 3 for different collisions (pp, p–Pb, Au–Au, Pb–Pb and Xe–Xe), for $\rho^0/\pi$, $K^0/\Lambda$, $K^{*+}/\Lambda$, $\Lambda(1520)/\Lambda$, $\Sigma^0/\Xi$ and $\phi/K$. Short-lived resonances show a sizable dependence on multiplicity. A clear suppression is observed for $\rho^0/\pi$ going from pp to Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [13]. The EPOS3 event generator [14], which includes UrQMD [15] for the late-stage hadronic cascade, is able to describe the evolution with multiplicity. The same behavior is observed in the $K^{*0}/K$ ratio, where the suppression is observed in a wider multiplicity range with data from pp at $\sqrt{s} = 7$ TeV, Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV.

The ratios of $\Sigma^{*+}/\Lambda$ and $\Lambda(1520)/\Lambda$ show flat behavior in small systems from pp and p–Pb collisions, and the results in Pb–Pb collisions show that $\Sigma^{*+}$ and $\Lambda(1520)$ are suppressed with respect to the $\Lambda$ production [16]. Finally, there is no significant centrality dependence of the $\Xi^{*0}/\Xi$ and $\phi/K$ ratios with multiplicity for all systems. This is expected in the context of
ratios of resonance and stable counterpart yields are reported as a function of multiplicity for the hadronic resonances, $\rho/\pi$, $K^{*0}/K$, $K^{*+}/K$, $\Sigma^{*+}/\Lambda$, $\Lambda(1520)/\Lambda$, $\Xi^{*0}/\Xi$, and $\phi/K$ from inelastic pp, p–Pb, Au–Au, Pb–Pb and Xe–Xe collisions. The error bars show the statistical uncertainty, while the empty and dark-shaded boxes show the total systematic uncertainty and the uncorrelated contribution across multiplicity bins, respectively. A comparison is also shown to the ratio predicted by the EPOS3 model for Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV, where the late hadronic cascade is simulated with UrQMD. STAR data are also shown for the $\Sigma^{*+}/\Lambda$ and $\Lambda(1520)/\Lambda$ ratios.

re-scattering, considering that the $\Xi^{*0}$ baryon and the $\phi$ meson live longer than the expected fireball lifetime, and therefore their decay daughters will not undergo re-scattering.

2.2 Energy dependence of resonance production

Figure 4 presents particle yield ratios of $K^{*0}/K$ (left) and $\phi/K$ (right) as a function of the center of mass energy per nucleon pair for different collision systems [17, 18]. On the left panel, the measurements of $K^{*0}/K$ from 7.7 GeV up to 5.02 TeV at various collision systems. The ratios in central collisions are observed to be smaller than the ratios from small collision systems such as pp and ee collisions. It is seen that there is no clear energy dependence from RHIC to LHC. The $\phi/K$ ratios are also independent of the energy of the collision and of the colliding system.

It has been argued that at lower energies below 7.7 GeV, the strangeness number needs to be conserved, which leads to a reduction in the yield of hadrons with a non-zero strangeness number. Since $\phi$ meson has zero net strangeness number ($S=0$), the $\phi/K$ ratio is expected to increase with decreasing collision energy in models using the canonical ensemble treatment for strangeness. The $\phi/K$ ratios are presented in Figure 5. In the left panel, the ratio decreases with increasing energy and saturates around 0.15 for $\sqrt{s_{NN}} \geq 5$ GeV. Purple curves depict statistical model calculations using strangeness correlation radius, $r_s$, values of 2.2 fm (dashed curve) and 4.2 fm (dashed-dotted curve). The green dotted curve corresponds to a tuned version of UrQMD. The recent measurement of the $\phi/K$ ratio at $\sqrt{s_{NN}} = 3$ GeV is presented...
Figure 3. Ratios of resonance and stable counterpart yields are reported as a function of multiplicity for the hadronic resonances, $\rho^0/\pi^-$, $K^*^0/K$, $K^*\pm/K$, $\Sigma^*\pm/\Lambda$, $\Lambda(1520)/\Lambda$, $\Xi^*^0/\Xi^-$, and $\phi/K$ from inelastic pp, p–Pb, Au–Au, Pb–Pb and Xe–Xe collisions. The error bars show the statistical uncertainty, while the empty and dark-shaded boxes show the total systematic uncertainty and the uncorrelated contribution across multiplicity bins, respectively. A comparison is also shown to the ratio predicted by the EPOS3 model for Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV, where the late hadronic cascade is simulated with UrQMD. STAR data are also shown for the $\Sigma^*\pm/\Lambda$ and $\Lambda(1520)/\Lambda$ ratios.

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3 Summary

A system size and energy dependence of resonance productions are presented. The yield ratios of $K^*(892)^0/K$ and $\phi/K$ have been measured in different collision systems from various experiments. The $K^*(892)^0/K$ ratio is more suppressed for the larger system. The suppression in the right panel of Figure 5. The grey solid line represents a THERMUS calculation based on the Grand Canonical Ensemble (GCE), while the dotted lines depict calculations based on the Canonical Ensemble (CE) with different values of $r_c$. The green dashed line, green shaded band, and solid red line show transport model calculations from the public versions UrQMD1, modified UrQMD2, and SMASH, respectively [12]. The thermal model with the canonical ensemble (when $r_c \sim 2.7$ fm) gives a good description of the results at $\sqrt{s_{NN}} = 3$ GeV.
is observed for the short-lived resonance due to the dominance of re-scattering over regeneration and no suppression for the longer-lived resonances is found. In wide collision energy (10-10⁴ GeV), no energy dependence of K*(892)⁰/K and φ/K ratios have been observed. In the lower energies, the φ/K ratio increases with decreasing collision energy which is expected in models using the canonical ensemble treatment for strangeness. This proceeding is focused on resonance production in terms of system size and energy dependence only. In addition to these results, the measurements of resonances from various perspectives are very important to understand the strangeness production, spin alignment, in-medium energy loss, and chiral symmetry restoration in heavy-ion physics.

References