In-Medium Modifications of Low-Mass Vector Mesons in PHENIX at RHIC

Yuji Tsuchimoto\textsuperscript{\textcopyright} for the PHENIX collaboration

\textsuperscript{\textcopyright}Graduate School of Science, Hiroshima University, 1-3-1 Kagamiyama, Higashi-hiroshima, 739-8526, Japan

Abstract

Measurements at RHIC have established the creation of a Quark Gluon Plasma (QGP) in most central heavy-ion collisions. An important tool to understand properties of the QGP is study of the spectral shapes of low-mass vector mesons (LVM’s), $\rho$, $\omega$ and $\phi$, which can be modified in the medium by partial restoration of chiral symmetry. This modification may be accessed directly by measuring low-momentum LVM’s via their decays into lepton pairs inside the hot matter. Since leptons are not subject to the strong interaction, they do not rescatter on their way out of the medium. The PHENIX experiment at RHIC has measured LVM production at mid-rapidity in $p+p$, $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Mass peaks for the LVM’s have been observed in the di-electron invariant mass spectra with a resolution of 10 MeV/$c^2$ in all of the three collision systems. The extracted spectra, mass and width of $\omega$ and $\phi$ in $p+p$, $d+Au$ and $Au+Au$, in the leptonic and hadronic decay channels are reviewed. As the widths of the mesons may be affected in the medium, the branching ratios of various decay modes may also be modified from the values in vacuum. The relative branching ratio is compared between $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$, which may be sensitive to the mass modification due to the small Q-value of $\phi \rightarrow K^+K^-$. 

1. Introduction

QCD is a non-abelian quantum gauge theory which discrives the strong interaction. The QCD predicts that a Quark Gluon Plasma (QGP) is created at hot and/or dense nuclear matter. Recently, there are many experimental results suggesting that the QGP has been created in heavy ion collisions at RHIC. For the next task, we are on stage to study the properties of the QGP.

Within the framework of QCD, most of the ordinary hadronic mass is expected to be obtained via the spontaneous breaking of chiral symmetry [1]. This effective mass depends on the vacuum energy density, and it will vanish in hot and/or dense matter. Some model calculations predict mass modification of low-mass vector mesons (LVM’s) in medium [2, 3, 4, 5]. The mass may be affected and become lighter and the width may become wider in the hot medium.

LVM’s have both leptonic and hadronic decay channels. The hadronic decay channels have an advantage of larger branching ratios. However, hadrons from deep within the hot matter are scattered by the strong force, thereby loosing information of the original decay. On the other hand, as leptons are not subject to the strong interaction, leptonic probes can carry information of the vector mesons in medium. The most straight-forward and direct method to detect the mass modification is line-shape analysis on invariant mass spectra of daughter leptons of the LVM’s. KEK E325 collaboration has reported an excess on the lighter side of the LVM peaks on
2. Experiment

The LVM measurements presented in this contribution were obtained from the data samples accumulated by the PHENIX experiment during \( p+p \), \( d+Au \) and \( Au+Au \) collisions at \( \sqrt{\text{NN}} = 200 \text{ GeV} \) in 2003-2005 physics runs. LVM’s are measured in both of electronic and hadronic channels using the PHENIX central spectrometer, which measures fully identified hadrons, electrons and photons [8]. Charged particles are tracked by drift chambers and pad chambers which provide momentum of the charged particles. Kaons are identified by the time of flight information measured by ToF counters (Full-PID method). For higher \( p_T \) kaons, the \( \phi \) can be also reconstructed without kaon identification (no-PID method). Electrons and positrons are identified by Čerenkov emission in RICH detectors, and by the ratio of momentum to energy measured by electromagnetic calorimeters. \( \rho/\omega/\phi \rightarrow e^+e^- \) are reconstructed by \( e^+e^- \) pairs. Photons are measured by the calorimeters, \( \pi^0 \rightarrow 2\gamma \) are reconstructed from \( 2\gamma \), and \( \omega \rightarrow \pi^0\gamma \) are from \( 3\gamma \).

3. Results

Figures 1 and 2 show invariant mass spectra of \( e^+e^- \) and \( K^+K^- \) in (a) \( p+p \), (b) \( d+Au \) and (c) \( Au+Au \) collisions, respectively. Clear peaks of \( \omega \) and \( \phi \) are seen in the \( e^+e^- \) mass spectra, as well as peaks of \( \phi \) in the \( K^+K^- \) mass spectra. The solid lines are the best fits of sums of mesons’ components. While relatively large modification is predicted on \( \omega \), there is inseparable \( \rho \) contribution in this mass region of the \( e^+e^- \) invariant mass spectra. \( \phi \) is a cleaner probe, despite relatively small modification expected, because there is no overlapping contribution of other resonances. In case of \( d+Au \), there is a more combinatorial background. Although with
Figure 2: Invariant mass of $K^+K^-$ pairs detected by the PHENIX central spectrometers in $p+p$ (a), $d+Au$ (b) and $Au+Au$ (c) collisions at $\sqrt{s_{NN}}=200$ GeV. The $\phi$ resonances clearly visible at 1.02 GeV/$c^2$ in these plots. Combinatorial backgrounds are estimated by event mixing.

Figure 3: Corrected $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ spectra as measured in (a) $p+p$ and $d+Au$ and (b) $Au+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV. The solid line in (a) is a fit to a Levy function of both channels in $p+p$ collisions. The dashed lines in (a) and (b) are the fit scaled by $N_{coll}$ for the case of $d+Au$ and $Au+Au$. The $N_{coll}$ scaled $p+p$ is a reasonable fit to the $d+Au$ spectra.

limited statistics, peaks of $\omega$ and $\phi$ in $e^+e^-$ and $\phi$ in $K^+K^-$ are seen in the mass spectra. In case of $Au+Au$, while there is a huge background, a peak of $\phi$ is seen in the $K^+K^-$ invariant mass spectra, and the peaks of $\phi$ and $\omega$ are seen in $e^+e^-$ after precise subtraction of the combinatorial background. Though we may apply line-shape analysis if we had more statistics, it is difficult with the present data samples.

The number of $\phi$ and $\omega$ are counted in the mass regions, and corrected for the acceptance and efficiency. Figure 3 shows the corrected $m_T$ spectra of $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ in $p+p$ and $d+Au$ collisions and (b) in each centrality of $Au+Au$ collisions, where the solid lines are global fits for $\phi \rightarrow K^+K^-$ and $e^+e^-$, and dashed lines show the yield in $p+p$ scaled by the number of binary nucleon-nucleon collisions ($N_{coll}$) for each collision centrality. The spectra of $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ are consistent with each other in all collisions.

In case of $d+Au$, the yield is slightly higher than the scaling line. This is a well-known nuclear effect called Cronin effect. In case of $Au+Au$, the yield is suppressed in the most central collisions at least in the $K^+K^-$ channel. The details of the $\phi$ suppression is reported in another talk [9]. As mentioned in the introduction, the branching ratio of $\phi \rightarrow K^+K^-$ to $e^+e^-$ is an important measurement. A change of the ratio may be seen as a difference in these spectra. Something interesting may be expected at low momentum in the central collisions. More statistics and careful analysis are needed to discuss a possible difference in the central collisions.

We also measured $\omega \rightarrow e^+e^-$ and $\pi^0\gamma$. Figure 4 (a) shows an invariant mass spectra of $3\gamma$ in...
Au+Au collisions. \( \omega \) is seen at high \( p_T \) in Au+Au collisions in the \( \pi^0 \gamma \) channel. Figure 4(b) and (c) show corrected \( m_T \) spectra of \( \omega \rightarrow e^+e^- \) and \( \omega \rightarrow \pi^0 \gamma \) in \( p+p \), \( d+Au \) and Au+Au collisions, where solid line is a global fit for \( \omega \) in \( p+p \), and dashed lines show the yield in \( p+p \) scaled by \( N_{\text{coll}} \) for each centrality. They agree with the \( N_{\text{coll}} \) scaling, while suppression may be seen in the most central collisions.

4. Summary and Outlook

In-medium modification of low-mass vector mesons is one of the best probes to study chiral symmetry restoration in hot and/or dense matter. We measured productions of \( \phi \) and \( \omega \) mesons via electronic and hadronic decay channels in \( p+p \), \( d+Au \) and Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV}/c \) in PHENIX. The production is consistent with each other in the both decay channels, and agree with the \( N_{\text{coll}} \) scaling. These systematic measurement methods for the LVM’s are highly established in PHENIX. A higher statistics run with a HBD detector, which has a capability to reject the \( \pi^0 \) dalitz background, will enable measurements in central Au+Au collisions and is planned at the end of this year. The data of the run may increase the accuracy of the LVM measurement significantly.

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