Debsankar Mukhopadhyay for the PHENIX collaboration†
Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37235, USA

Abstract.
We present the results on the mid-rapidity $\phi$ meson production in the $K^+K^-$ decay channel in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the PHENIX experiment at RHIC. The spectral shape of the $\phi$ resonance, studied at different collision centralities, is consistent with the particle data book. The transverse mass spectra are measured in four centrality bins. The inverse slopes ($T$), yields ($dN/dy$) and particle ratios are studied as a function of centrality. The nuclear modification factor is measured through the ratio, $R_{CP}$, of central to peripheral yields normalized to the number of nucleon-nucleon collisions. The $R_{CP}$ of the $\phi$ mesons is less than unity and is comparable to that of pions rather than $R_{CP}\sim 1$ observed for protons and anti-protons.

1. Introduction

Heavy ion collisions at relativistic energies may lead to the formation of a Quark-Gluon Plasma (QGP) in which chiral symmetry is restored and nuclear matter is deconfined. Theory predicts[1] that the chiral symmetry restoration may influence strongly the spectral shape (centroid and width) of the $\phi$ meson. Since the mass of the $\phi$ meson is close to twice the kaon mass, a modification in the $\phi$ mass centroid can lead to an observable imbalance in the branching ratios of the $\phi$ into kaon and di-lepton decay channels[2]. Consisting of $s\bar{s}$ pair, the $\phi$ production in heavy ion collisions is sensitive to the strangeness enhancement.

The PHENIX experiment at RHIC has $\phi$ mass resolution that is better than or comparable to the natural width of $\phi$. Thus, it can detect the predicted medium modifications of the $\phi$ mass and width, should they occur. The data presented here are from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and are obtained using the $K^+K^-$ decay channel. We present the centrality dependence of line shape, yields, inverse slopes and particle ratios. The nuclear modification factor $R_{CP}$ of $\phi$ mesons is also obtained and compared to that of pions and protons.

† See Appendix for the full collaboration list.
2. Experiment, data selection and techniques

The present analysis is based on the measurements performed using the east arm of the PHENIX spectrometer [3]. Particles are identified by their mass after determining their momenta and velocities. The momentum measurements are provided by a multi-layer drift chamber and a layer of pad chambers. The velocities are obtained through time-of-flight (TOF) measurements. Two detector systems are used for TOF measurements: a TOF scintillator wall covering $\Delta \phi \approx \pi/8$ and a lead scintillator electromagnetic calorimeter ($\Delta \phi \approx \pi/4$). The PHENIX east arm covers pseudo-rapidity $|\Delta \eta| < 0.35$. The collision vertex is measured by the Beam-beam counters (BBC) and the centrality is determined by the BBC along with the Zero Degree Calorimeter. We have used $20 \times 10^6$ minimum bias events within $|z_{vertex}| < 30$ cm.

The $\phi$ mesons are reconstructed by forming the $K^+K^-$ invariant mass distributions. A large combinatorial background is inherent to the same event $K^+K^-$ pair invariant mass distribution. The combinatorial background is estimated by the event mixing technique which is described in details at ref.[4, 5]. The $\phi$ signal is extracted by subtracting the combinatorial background from the same event pairs.

3. Results

3.1. Centroid and width analysis

The Figure 1 shows the $\phi$ meson invariant mass distribution in $K^+K^-$ decay channel for the minimum bias events. The upper panel of the figure shows the same event and combinatorial pair invariant mass distributions, while the lower panel presents the subtracted $\phi$ mass spectrum where the combinatorial background beyond the $\phi$ peak is essentially zero. The $\phi$ meson invariant mass peak is fitted with a relativistic Breit Wigner (RBW) distribution convolved with a Gaussian experimental $\phi$ mass resolution function with $\sigma = 1.0$ MeV/c$^2$, which is determined by a Monte Carlo simulation. The fitted minimum bias mass centroid and width, shown on the bottom panel of the figure, are found to be consistent with the PDG values [6].

The centroids and widths are further studied as the function of centrality in Figure 2. The left panel of the figure shows the centrality dependence of the fitted centroids. The upper and lower 1$\sigma$ systematic error limits are indicated. The dotted line shows the PDG mass centroid. The solid line indicates the result obtained with a one-parameter constant fit through the measured data points. We observe that the centroid of the $\phi$ meson resonance is consistent with the PDG values within errors. The $\phi$ mass widths (right) are studied at different centralities. The error bar on each point shows the statistical error, while the bands on the points indicate the systematic errors. The dotted line shows the PDG $\phi$ mass width. The solid line shows the results of the constant fit assumption to the data points. Again, within the experimental errors, there is no convincing evidence of a variation of the $\phi$ width as a function of centrality.
Figure 1. Minimum-bias $\phi \to K^+K^-$ invariant mass spectrum using the kaons identified in the PHENIX detector. The top panel shows the same event (circles) and combinatorial background $K^+K^-$ mass distributions. The bottom panel shows the subtracted mass spectrum fitted with Relativistic Breit-Wigner function convolved with the Gaussian experimental resolution function.

Figure 2. Centrality dependence of the $\phi$ mass centroid (left) and $\phi$ intrinsic width (right).
3.2. Transverse mass spectra, yields and ratios

The transverse mass spectra of the $\phi$ mesons are studied for the minimum bias and three centrality classes, namely, 0 - 10%, 10 - 40% and 40 - 92%. The invariant yields in different $m_T$ bins are obtained by correcting the measured signal for geometrical acceptance and occupancy \[5\]. Each $m_T$ spectrum is then fitted with an exponential function in $m_T$ to extract $dN/dy$ and inverse slope, $T$ as two fitting parameters. Figure 3 shows the transverse mass spectra of $\phi$ mesons for above four centrality selections.

Figure 3. $m_T$ spectra of $\phi$ mesons for 0 – 10%, 10 – 40%, 40 – 92% and minimum-bias (0 - 92%) centrality classes.

The centrality dependence of $dN/dy$ is plotted in Figure 4. The left panel shows a steady increase in $dN/dy$ with the number of participants. In the right panel, the yield is normalized to the number of participant pairs to take into account the size of the system. Within the error bars this normalized rapidity density is approximately independent of centrality with a possible slight increase from peripheral to the mid-peripheral collisions. The trend is quite different from lower energy results measured at the AGS. In \[7\], the yield of $\phi$ was reported to be increasing faster than linearly with the number of participants.

The extent and mechanism of strangeness enhancement are investigated via ratios $\phi/\pi$ and $\phi/K$ at different centralities as shown in Figure 5 (c) - (d) The $\phi/K$ ratio, in this limited number of centrality bins, is approximately flat as a function of centrality. The possibility of structure in the $\phi/\pi$ ratio is difficult to infer from our data within the error bars. For comparison, the ratios $K^+/\pi^+$ and $K^-/\pi^-$ are also shown in Figure 5 (panels (a) and (b)). Since these ratios clearly increase with $N_{part}$, $\phi/K$ and $\phi/\pi$ can not be both flat. Analysis of the significantly larger data set from Run4 of RHIC will be needed to map out the centrality dependence of these ratios.

The inverse slope, $T$, is found to be independent of collision centrality as shown in Figure 6. This result may be (wrongly) interpreted as an indication that the $\phi$-mesons do not participate in radial flow as the other hadrons. However, we note that our measurement does not extend down to low $m_T$ which is the region of the spectra that
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gets affected by radial flow. A hydrodynamics fit \cite{5} to the spectra of $\pi^{\pm}, K^{\pm}, p$ and $\bar{p}$ gives a satisfactory description of the $\phi$ spectra, too.

3.3. Nuclear Modification Factor, $R_{CP}$

In order to understand the particle production mechanism at the intermediate $p_T$ region, especially whether it is dominated by the mass of the particles or their quark contents, it is important to study the nuclear modification factor, $R_{CP}$, which is a ratio of the invariant yields normalized to the number of collisions in central and peripheral collisions, as a function of $p_T$. The nuclear modification factor shows distinctive behavior for pions (mesons) and protons (baryons) \cite{8}. Pions are suppressed, as expected from jet-quenching in the dense medium produced in the collisions, while (anti)proton production shows scaling typical for point-like processes in the absence of medium modifications. These seemingly contradictory results point to different dominant production mechanisms of pions and protons at moderately high $p_T$. The measurement of $\phi$ meson $R_{CP}$ provides a stringent test of theories that invoke the particle mass to explain pion/proton difference. In Figure 7 we observe that $R_{CP}$ of the $\phi$ mesons is comparable to that of pions rather than protons, which have similar mass. This result may imply that the dominant hadron production mechanism at intermediate $p_T$ is sensitive to the quark content of the particles \cite{9,10}.
Figure 5. Centrality dependence of particle ratios for (a) $K^+ / \pi^+$, (b) $K^- / \pi^-$, (c) $\phi / 0.5 (\pi^+ + \pi^-)$ (scaled by a factor of 5), (d) $\phi / 0.5 (K^+ + K^-)$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 6. Centrality dependence of the inverse slope, T.
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![Graph showing the scaled central to peripheral ratio $R_{CP}$ for $(p+p)/2$, $\pi^0$, and $\phi$. The vertical dotted bar on the right represents the error on $N_{coll}^{0-10%}/N_{coll}^{40-92%}$. The shaded solid bar around $R_{CP} = 1$ represents 12% systematic error which can move the proton and/or $\phi$ points with respect to one another. The dotted horizontal line at $R_{CP} = 0.62$ is a straight line fit to the $\phi$ data.]

4. Summary

We have performed a systematic study of the φ meson production at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The spectral shape of the φ resonance is found to be consistent with PDG measured values. The yield, $dN/dy$, of the φ increases steadily with centrality from $0.318 \pm 0.028$(stat)±0.051(syst) in peripheral collisions to $3.94 \pm 0.60$(stat)±0.62(syst) in central collisions. In the measured range ($m_T - m_\phi > 0.4$ GeV), the inverse slope is essentially independent of the collision centrality. The nuclear modification factor for the φ mesons is consistent with that of pions probably indicating a different particle production process for mesons and baryons at intermediate $p_T$.

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