Spin alignment measurements of the K*(0)(892) and phi(1020) vector mesons in heavy ion collisions at root S-NN=200 GeV

This paper is posted at Purdue e-Pubs.
http://docs.lib.purdue.edu/physics_articles/759
Spin alignment measurements of the $K^*(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

We present the first spin alignment measurements for the $K^{*0}(892)$ and $\phi(1020)$ vector mesons produced at midrapidity with transverse momenta up to 5 GeV/$c$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC. The diagonal spin-density matrix elements with respect to the reaction plane in $Au + Au$ collisions are $\rho_{00} = 0.32 \pm 0.04 \text{ (stat)} \pm 0.09 \text{ (syst)}$ for the $K^{*0}$ ($0.8 < p_T < 5.0$ GeV/$c$) and $\rho_{00} = 0.34 \pm 0.02 \text{ (stat)} \pm 0.03 \text{ (syst)}$ for the $\phi$ ($0.4 < p_T < 5.0$ GeV/$c$) and are constant with transverse momentum and collision centrality. The data are consistent with the unpolarized expectation of $1/3$ and thus no evidence is found for the transfer of the orbital angular momentum of the colliding system to the vector-meson spins. Spin alignments for $K^{*0}$ and $\phi$ in $Au + Au$ collisions were also measured with respect to the particle’s production plane. The $\phi$ result, $\rho_{00} = 0.41 \pm 0.02 \text{ (stat)} \pm 0.04 \text{ (syst)}$, is consistent with that in $p+p$ collisions, $\rho_{00} = 0.39 \pm 0.03 \text{ (stat)} \pm 0.06 \text{ (syst)}$, also measured in this work. The measurements thus constrain the possible size of polarization phenomena in the production dynamics of vector mesons.

DOI: 10.1103/PhysRevC.77.061902 PACS number(s): 24.70.+s, 25.75.Nq
Spin alignment is described by a spin-density matrix $\rho$, a $3 \times 3$ Hermitian matrix with unit trace. A deviation of the diagonal elements $\rho_{mn}(m = -1, 0, 1)$ from $1/3$ signals net spin alignment. Because vector mesons decay strongly, the diagonal elements $\rho_{-1,-1}$ and $\rho_{1,1}$ are degenerate and $\rho_{00}$ is the only independent observable. It can be determined from the angular distribution of the decay products [22],

$$\frac{dN}{d(\cos \theta^*)} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1) \cos^2 \theta^*],$$  

(1)

where $N_0$ is the normalization and $\theta^*$ is the angle between the polarization direction $\hat{n}$ and the momentum direction of a daughter particle in the rest frame of the parent vector meson. In the case of a global spin alignment measurement, the polarization direction $\hat{n}$ lies along the orbital angular momentum of the colliding system. It is determined by the reaction plane, requiring only the second-order term because Eq. (1) is invariant under $\theta^* \rightarrow \pi + \theta^*$ [23]. For the production plane measurement, $\hat{n}$ lies along the normal to the production plane, which is determined by the momentum of the vector meson and of the colliding beams.

Vector mesons are expected to originate predominantly from primordial production [24,25], unlike hyperon production, which is expected to have large resonance decay contributions [21,24,25]. Another difference between the present spin alignment measurement and our recent measurement of global hyperon polarization [21] is that contributions to a spin alignment measurement are generally additive, whereas contributions along a polarization direction may cancel. Last, as far as the reaction plane resolution is concerned, the aforementioned method has an advantage over the method used in Ref. [21], where the reaction plane was estimated in forward detectors.

A total of approximately $2.3 \times 10^7$ events from Au + Au data collection in the year 2004 run and $6.0 \times 10^6$ events from $p+p$ data collection in the year 2001 run have been used in these analyses. The events were collected with minimum bias triggers [26,27]. Charged tracks were reconstructed with the STAR Time Projection Chamber (TPC) for pseudorapidities $|\eta| < 1.0$ and all azimuthal angles [28]. Particle identification is achieved by correlating the ionization energy loss $dE/dx$ of charged particles in the TPC gas with their measured momenta. The measured $dE/dx$ is reasonably well described by the Bichsel function smeared with a resolution of width $\sigma$ [29]. By measuring the $dE/dx$, pions and kaons could be identified up to a momentum of about 0.6 GeV/c, whereas protons could be separated from pions and kaons up to a momentum of about 1.1 GeV/c. Tracks within 2$\sigma$ of the pion/kaon Bichsel curve were selected in the analyses. The $K^{*0}$ and $\phi$ mesons were reconstructed through their respective hadronic decay channels, $K^{*0} \rightarrow K^+\pi^-$, $K^{*0} \rightarrow K^0\pi^+$, and $\phi \rightarrow K^+K^-$. The $K^{*0}$ and $K^{*0}$ samples were combined to enhance the statistics and the term $K^{*0}$ in the remainder of this Rapid Communication will refer to the combined sample. The collision centrality was determined by the charged hadron multiplicity within $|\eta| < 0.5$. The same analysis techniques have been used in our earlier measurements of $K^{*0}$ and $\phi$ production [26,27].
Figure 1 illustrates aspects of the analysis and its results for particular $p_T$ bins. The top panels show the invariant mass distributions for (a) $K^{*0}$ and (b) $\phi$ candidates in midcentral (20–60%) Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, including all values of $\cos \theta^*$. In these analyses invariant mass distributions were obtained for $K^{*0}$ and $\phi$ for each $\cos \theta^*$ and $p_T$ interval. The raw $K^{*0}$ and $\phi$ yields in each of these distributions were obtained by subtracting the corresponding combinatorial backgrounds and fitting the remaining distributions with a Breit-Wigner function plus a polynomial curve to describe the residual background. The raw yields were then corrected for detection efficiency and acceptance determined from Monte Carlo GEANT simulations [26,27]. The middle panels in Fig. 1 show the $\cos \theta^*$ distributions, after efficiency and acceptance corrections, for the (c) $K^{*0}$ and (d) $\phi$, respectively. Equation (1) was fitted to these distributions to determine $\rho_{00}(p_T)$. In the analyses, we used charged particle tracks with $0.2 < p_T < 2.0$ GeV/c and pseudorapidity $|\eta| < 1.0$ originating from the primary interaction vertex to reconstruct the event plane as an estimate of the reaction plane [30]. Tracks associated with a $K^{*0}$ or a $\phi$ candidate are explicitly excluded from the event plane calculation. The results for $\rho_{00}(p_T)$ were corrected for the finite event plane resolution, which was determined by correlating two random subevents. The correction factor on $(3\rho_{00} - 1)$ is determined to be 1/0.81 in 20–60% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [30]. The bottom panels, Figs. 1(e)–1(g), represent the $\cos \theta^*$ distribution for $K^{*0}$ and $\phi$ mesons with respect to the production plane in Au + Au and $p+p$ collisions. In this case, $\rho_{00}(p_T)$ is extracted directly by fitting Eq. (1) to the distributions. We have checked our analysis procedure by extracting $\rho_{00}$ for the abundantly produced, but spinless $K_S^0$ meson ($J^P = 0^-$). The results are shown in Fig. 1(h) and are consistent with 1/3 within the statistical uncertainties, as expected. The $\chi^2/ndf$ value is unsatisfactory for the $K_S^0$ fit for $0.4 < p_T < 0.8$ GeV/c, which is indicative of point-to-point systematics. It reaches satisfactory values at larger $p_T$.

The measurements of the $K^{*0}$ and $\phi$ global spin alignment versus $p_T$ of the vector meson for midcentral Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented in Fig. 2, and are summarized in Table I. Both statistical and systematic uncertainties are shown. The dominant contribution to the systematic uncertainty for the $\phi$ ($K^{*0}$) meson ranges from 0.020 (0.05) to 0.045 (0.10), originating from uncertainty in the magnitude and shape of the residual background after the subtraction of combinatorial background. This residual arises from the incomplete description of combinatorial background via the event mixing technique and from distortions to the background.

Table I. The averaged spin-density matrix elements $\rho_{00}$ with respect to the reaction plane in midcentral Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

<table>
<thead>
<tr>
<th>$K^{*0}$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{00}(p_T &lt; 2.0$ GeV/c)</td>
<td>0.31 ± 0.04 ± 0.09</td>
</tr>
<tr>
<td>$\rho_{00}(p_T &gt; 2.0$ GeV/c)</td>
<td>0.37 ± 0.04 ± 0.09</td>
</tr>
<tr>
<td>$\rho_{00}(p_T &lt; 5.0$ GeV/c)</td>
<td>0.32 ± 0.03 ± 0.09</td>
</tr>
</tbody>
</table>

FIG. 1. (Color online) The invariant mass distribution after combinatorial background subtraction for (a) the $K^{*0}$ and (b) the $\phi$ meson in midcentral Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, including all values of $\cos \theta^*$. The continuous lines represent fits of signal, described with a Breit-Wigner function, and residual background, described with the dashed polynomial curves. Panels (c) and (e) and panels (d) and (f) represent the $\cos \theta^*$ distributions for the $K^{*0}$ and $\phi$ yields in Au + Au collisions, respectively. Panel (g) is the $\phi$ yield in $p+p$ collisions, whereas panel (h) shows the control measurement of the spin-less $K_S^0$ meson $\cos \theta^*$ distribution. The error bars show statistical uncertainties. The blue dashed lines in (c)–(h) are fits of Eq. (1) to the data.
in the invariant mass distribution near the $\phi$ peak caused by photon conversions and other correlated backgrounds such as $K^{0}\rightarrow K^{+}\pi^{-}, \pi^{0}\rightarrow \pi^{+}\pi^{-}, \Lambda \rightarrow p\pi^{-}$, and $\Delta \rightarrow N\pi$ decays [31]. In the case of the $K^{*0}$ these backgrounds include $K_{S}^{0}\rightarrow \pi^{+}\pi^{-}, \rho^{0}\rightarrow \pi^{+}\pi^{-}, \phi \rightarrow K^{+}K^{-}, \Lambda \rightarrow p\pi^{-},$ and $\Delta \rightarrow N\pi$ decays [32]. Other point-to-point systematic uncertainty associated with particle identification for the $K(400)$ meson were estimated to range from $0.007$ (0.06) to $0.012$ (0.09) by tightening the $K^{\pm}(\pi$ and $K)$ $\langle dE/dx \rangle$ cut from $2\sigma$ to $1\sigma$. An additional sizable contribution to the $\phi$ uncertainty was estimated to range from $0.007$ to $0.012$ by varying the fitted invariant mass range from $1.00-1.04$ GeV/c$^2$ to $1.00-1.06$ GeV/c$^2$ and to the $K^{*0}$ uncertainty ranging from $0.02$ to $0.05$ by changing its analyzed rapidity range from $|y| < 1$ to $|y| < 0.5$. The systematic uncertainties in the $K^{*0}$ measurements are larger than those in the $\phi$ measurement mainly because of the lower signal-to-background ratio of $\sim$1/1000 compared to $\sim$1/25 for the $\phi$ meson. The contributions to the systematic uncertainty caused by elliptic flow effects and the event plane resolution are found to be negligible. The $K^{*0}$ and $\phi$ data are consistent with each other and are consistent with $1/3$ at all $p_T$.

Hadronization of globally polarized thermal quarks, typically having $p_T < 1$ GeV/c, in midcentral Au + Au collisions is predicted to cause $p_T$-dependent deviations of $\rho_{00}$ from the unpolarized value of $1/3$ [1,4,6,33]. Recombination of polarized thermal quarks and antiquarks is expected to dominate for $p_T < 2$ GeV/c and to lead to values of $\rho_{00} < 1/3$ as indicated in Fig. 2 for a typical range of expected light (strange) quark polarizations $P_{\phi,s}$ [6]. The fragmentation of polarized thermal quarks with larger $p_T$, however, would lead to values of $\rho_{00} > 1/3$ for $1 < p_T < 3$ GeV/c [6,33], which is indicated as well. In the region of $1 < p_T < 2$ GeV/c both hadronization mechanisms could occur and their effects on $\rho_{00}$ may cancel. As observed in Fig. 2 these effects are predicted to be smaller than our experiment sensitivity. However, the large

<table>
<thead>
<tr>
<th>$K^{*0}$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{00}(p_T &lt; 2.0$ GeV/c)</td>
<td>$0.43 \pm 0.04 \pm 0.09$</td>
</tr>
<tr>
<td>$\rho_{00}(p_T &gt; 2.0$ GeV/c)</td>
<td>$0.38 \pm 0.04 \pm 0.09$</td>
</tr>
<tr>
<td>$\rho_{00}(p_T &lt; 5.0$ GeV/c)</td>
<td>$0.42 \pm 0.03 \pm 0.09$</td>
</tr>
<tr>
<td>$\rho_{00}(p + p)$</td>
<td>$0.39 \pm 0.03 \pm 0.06$</td>
</tr>
</tbody>
</table>
The $K^{*0}$ meson, and the statistical uncertainties are somewhat smaller than the systematic uncertainty estimates. The $\phi$ point-to-point systematic uncertainty estimate includes a dominant contribution ranging from 0.030 to 0.045 due to residual background plus two smaller contributions of 0.006–0.012 and 0.005–0.010 estimated by varying the background plus two smaller contributions of 0.006–0.012 contribution ranging from 0.030 to 0.045 due to residual systematic uncertainty estimate includes a dominant smaller than the systematic uncertainty estimates. The $\phi$ contribution ranging from 0.02 to 0.08 and about equal contributions ranging from 0.01 to 0.08 by varying particle identification criteria and analyzed rapidity. The $Au+Au$ data for $\rho_{00}$ are consistent with 1/3 to within 1–2 times the total uncertainties, although the central values tend to increase with decreasing $p_T$ for $p_T < 2.0$ GeV/$c$. The $p+p$ results are consistent with the $Au+Au$ results and with 1/3. No conclusive evidence is found for large polarization phenomena in the production dynamics of vector mesons in the covered kinematic region with the precision of current measurements. The $p+p$ results are in qualitative agreement with the suggested relation of vector-meson spin alignment with respect to the production plane and the null results observed for the transverse spin asymmetries in singly polarized $p+p$ collisions at midrapidity [19,20]. OPAL and DELPHI have previously reported similar null results for the spin alignment of the $K^{*0}$ and $\phi$ mesons produced with small fractional momenta ($x_F < 0.3, x_p = p/p_{beam}$) in $e^+e^-$ collisions [13,14], although the production and fragmentation processes involved there are different from those at RHIC.

In summary, we have presented the first measurements of spin alignment for $K^{*0}$ and $\phi$ vector mesons at midrapidity at RHIC. The results for the diagonal spin-density matrix element $\rho_{00}$ with respect to the reaction plane in $Au+Au$ collisions are found to be constant with $p_T$ in the measured region, covering up to 5 GeV/$c$, and constant with centrality. The data are consistent with the unpolarized expectation of 1/3 and thus provide no evidence for global spin alignment despite the large orbital angular momentum in noncentral $Au+Au$ collisions at RHIC. The results with respect to the production plane are found to be less than 2 standard deviations above 1/3 in $Au+Au$ collisions and are consistent with the results in $p+p$ collisions at the same collisions energy. The measurements thus constrain the possible size of polarization phenomena in the production dynamics of vector mesons. Future measurements of polarization with respect to the jet production plane are complementary to the current measurements because they are not sensitive to the initial conditions and may probe the system’s mean free path [2].

We thank the RHIC Operations Group and RCF at BNL and the NERSC Center at LBNL and the resources provided by the Open Science Grid consortium for their support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science; the U.S. NSF; the Sloan Foundation; the BMBF of Germany; CNRS/IN2P3, RA, RPL, and EMN of France; EPSRC of the United Kingdom; FAPESP of Brazil; the Russian Ministry of Science and Technology; the NNSFC, CAS, MoST and MoE of China; IRP and GA of the Czech Republic; FOM of the Netherlands; DAE, DST, and CSIR of the Government of India; Swiss NSF; the Polish State Committee for Scientific Research; Slovak Research and Development Agency; and the Korea Science & Engineering Foundation.
