Search for the rare decays $J/\psi \to D^{*-}\rho^+$ and $J/\psi \to D^{0}\bar{K}^{*0}$


(BESIII Collaboration)

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A search for the rare decays of $J/\psi \to D^{*+}_s \rho^+ + c.c.$ and $J/\psi \to \bar{D}^0 \bar{K}^{*0} + c.c.$ is performed with a data sample of 225.3-million $J/\psi$ events collected with the Beijing Spectrometer III detector. No evident signal is observed. Upper limits on the branching fractions are determined to be $\mathcal{B}(J/\psi \to D^{*+}_s \rho^+ + c.c.) < 1.3 \times 10^{-5}$ and $\mathcal{B}(J/\psi \to \bar{D}^0 \bar{K}^{*0} + c.c.) < 2.5 \times 10^{-6}$ at the 90% confidence level.

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I. INTRODUCTION

The decays of the low-lying charmonium state $J/\psi$, which is below the open-charm threshold, are dominated by strong interactions through intermediate gluons and electromagnetic interactions through virtual photons, where both the intermediate gluons and photons are produced by $c\bar{c}$ annihilation. However, flavor-changing...
weak decays of $J/\psi$ through virtual intermediate bosons are also possible in the standard model (SM) framework, and the branching fractions of $J/\psi$ inclusive weak decays are estimated to be on the order of $10^{-8}$ [1]. Several models addressing new physics, including the top-color model, the minimal supersymmetric standard model (MSSM) with R-parity violation and a general two-Higgs doublet model (2HDM), allow $J/\psi$ flavor-changing processes to occur with branching fractions around $10^{-5}$, which may be measurable in experiments [2,3]. Searches for rare $J/\psi$ decays to a single charmed meson provide an experimental test of the SM and a way to look for possible new physics beyond the SM.

The BESII experiment has searched for semileptonic decays and hadronic decays of $J/\psi \rightarrow D^+_s\pi^+$, $J/\psi \rightarrow D^+\pi^+$, and $J/\psi \rightarrow \bar{D}^0K^0$ [4] and set upper limits on the branching fractions set at world average values [19], while the remaining unknown decay modes are modeled by LUNDCHARM [20].

III. DATA ANALYSIS

In order to avoid large background contamination from conventional $J/\psi$ hadronic decays, the $D^+_s$ and $\bar{D}^0$ mesons are identified by their semileptonic decays $D^+_s \rightarrow \phi e^-\bar{\nu}_e$ with $\phi \rightarrow K^+K^-$ and $\bar{D}^0 \rightarrow K^- e^+\bar{\nu}_e$, where the electron is used to tag the events and the missing energy due to the escaping neutrino is also used to suppress backgrounds. Since the neutrinos are undetectable, the $D^+_s$ and $\bar{D}^0$ mesons cannot be directly identified by their invariant mass of the decay products. However, because of the two-body final states, they can be identified in the distribution of mass recoiling against the $\rho^+$ and $K^{*0}$ in $\rho^+ \rightarrow \pi^+\pi^0(\pi^0 \rightarrow \gamma\gamma)$ and $K^{*0} \rightarrow K^-\pi^+$ decays, respectively.

Charged tracks in BESIII are reconstructed from MDC hits. For each charged track, the polar angle must satisfy $|\cos \theta| < 0.93$, and it must pass within $\pm 20$ cm from the interaction point in the beam direction and within $\pm 2$ cm of the beam line in the plane perpendicular to the beam. The number of charged tracks is required to be four with zero net charge. The TOF and the specific energy loss $dE/dx$ of a particle measured in the MDC are combined to calculate particle identification (ID) probabilities $\text{Prob}(i)$, where $i = \{e, \pi, K/p\}$ is the particle type. $\text{Prob}(K) > \text{Prob}(\pi)$ and $\text{Prob}(K) > \text{Prob}(p)$ are required for kaon candidates, while $\text{Prob}(\pi) > \text{Prob}(e)$, $\text{Prob}(\pi) > \text{Prob}(K)$ and $\text{Prob}(\pi) > \text{Prob}(p)$ are required for pion candidates. For electron candidates, besides the particle identification requirement of $\text{Prob}(e) > \text{Prob}(\pi)$ and $\text{Prob}(e) > \text{Prob}(K)$, $E/cP > 0.8$ is also required, where $E/cP$ is the ratio of the energy deposited in the EMC to the momentum reconstructed from the MDC. In addition, $|\cos \theta| < 0.8$ is required for electron candidates since the particle ID efficiencies between data and MC agree better in the barrel.

Photon candidates are reconstructed by clustering EMC crystal energies. Efficiency and energy resolution are improved by including energy deposits in nearby TOF counters. A photon candidate has to be more than $20^\circ$ away from any charged track, and the minimum energy is $25$ MeV for barrel showers ($|\cos \theta| < 0.80$) and $50$ MeV for end cap showers ($0.86 < |\cos \theta| < 0.92$). An EMC timing requirement, i.e., $0 \leq t \leq 700$ ns, is used to suppress electronic noise and energy deposits in the EMC unrelated to the
the one yielding the smallest $\rho$ used to select the signal.

The momentum of the missing neutrino, $P_{\nu}$, is determined from the difference between the net four-momentum of the $\gamma\gamma$ candidates in addition to the charged tracks. If there is a $\pi^0$ candidate with $x_{\gamma\gamma}^2 < 20$, the event is vetoed. The $K^-\pi^+$ invariant mass distribution is shown in Fig. 2(b). To select $K^0$ candidates, the $K^-\pi^+$ invariant mass is required to satisfy $M_{K^-\pi^+} \in (0.82, 0.98)$ GeV/c$^2$. The $P_{\text{miss}} > 0.1$ GeV/c and $|U_{\text{miss}}| < 0.02$ GeV requirements are also used to suppress the backgrounds with $e/\pi$ misidentification or multiphotons in the final states, and their distributions are

$$|U_{\text{miss}}| < 0.02 \text{ GeV}.$$

FIG. 2 (color online). The invariant mass distributions of resonance candidates for (a) $\rho^+$ from $J/\psi \rightarrow D^-\rho^+$, $\rho^+ \rightarrow \pi^+\pi^0(\pi^0 \rightarrow \gamma\gamma)$ and (b) $\bar{K}^0$ from $J/\psi \rightarrow \bar{D}^0K^0$, $\bar{K}^0 \rightarrow K^-\pi^+$. The requirements of $M_{\pi^+\pi^0} \in (0.62, 0.95)$ GeV/c$^2$ and $M_{K^-\pi^+} \in (0.82, 0.98)$ GeV/c$^2$ are shown in the figures by vertical arrows. The dots with error bars are data, while the histograms represent distributions of the arbitrarily normalized exclusive signal MC events.

FIG. 3 (color online). $P_{\text{miss}}$ distributions for the decay of (a) $J/\psi \rightarrow D^-\rho^+$ and (b) $J/\psi \rightarrow \bar{D}^0\bar{K}^0$. The requirement $P_{\text{miss}} > 0.1$ GeV/c is shown in the figures by vertical arrows. The dots with error bars are data, while the histograms represent distributions of the arbitrarily normalized exclusive signal MC events.
shown in Figs. 3(b) and 4(b), respectively. After all selection criteria are applied, 11 events survive in the 
(1.82, 1.90) GeV/c$^2$ mass region in the distribution of 
mass recoiling against the $K^<0$, which is shown in Fig. 5(b). 
No accumulation of events in the signal region is found. 
MC simulations are used to determine mass resolutions 
and selection efficiencies and to study possible back-
grounds. Here, the backgrounds contributions are esti-
mated using $U_{miss}$ sidebands, defined as $U_{miss} \in (0.05, 0.10)$ GeV and $|U_{miss}| \in (0.08, 0.10)$ GeV for 
$J/\psi \rightarrow D^- \rho^+$ and $J/\psi \rightarrow \bar{D}^0 K^<0$, respectively. There are 15 and 9 sideband events surviving in the $D^-_s$ and $\bar{D}^0$ mass region. The number of surviving background events and their distributions from sideband data are also consistent with data.

IV. SYSTEMATIC ERRORS

In this analysis, the systematic errors in the determi-
nation of the branching fraction upper limits mainly come 
from the following sources:

(i) MDC tracking: The MDC tracking efficiency is 
studied in clean channels like $J/\psi \rightarrow \rho \pi \rightarrow \pi^+\pi^-\rho^0$, $J/\psi \rightarrow p \bar{p} \pi^+\pi^-$, and $J/\psi \rightarrow K^0_s K^+\pi^-$ samples [22]. It is found that the MC simulation agrees with data within 1.0% for each charged track. Therefore,
4.0% is taken as the systematic error on the tracking efficiency for the two channels analyzed with four charged tracks in the final states.

(ii) Photon detection: The photon detection efficiency is studied from $J/\psi \rightarrow \rho^0 \pi^0$ and photon conversion via $e^+ e^- \rightarrow \gamma \gamma$ [23]. The difference between the detection efficiencies of data and MC simulation is 1.0% for each photon.

(iii) Particle ID: The particle ID efficiencies of electrons, pions, and kaons are studied with samples of radiative Bhabha events, $J/\psi \rightarrow p \bar{p} \pi^+ \pi^-$, and $J/\psi \rightarrow K^0_S K^+ \pi^-$, respectively [22]. The kaon, pion, and electron particle ID efficiencies for data agree with MC simulation within 1% for each charged particle, and 4% is taken as the systematic error from this source.

(iv) $\pi^0$ kinematic fit: To estimate the systematic error from the $\pi^0$ kinematic fit in the analysis of $J/\psi \rightarrow D_s^+ \rho^+$, a clean $\pi^0$ sample is selected from $J/\psi \rightarrow \rho^+ \pi^- (\rho^+ \rightarrow \pi^0 \pi^0)$ without the kinematic fit. Events with two oppositely charged tracks identified as pions and two photons are selected. Further, the $\pi^-$ momentum is required to be in the range of $P_{\pi^-} \in (1.4, 1.5)$ GeV/c, and the $\pi^+ \pi^- \pi^0$ invariant mass is required to be in the $J/\psi$ mass region $|M_{\pi^+ \pi^- \pi^0} - M_{J/\psi}| < 0.05$ GeV/c$^2$. In addition, $E/cP$ is required to be less than 0.8 to remove Bhabha events.

After the above selection, a same $\pi^0$ kinematic fit as the one in the selection of $J/\psi \rightarrow D_s^+ \rho^+$ is done on the candidates. The same analysis is also performed with MC events. The efficiency difference between data and MC simulation due to the $\pi^0$ kinematic fit with $\chi^2 < 200$ is 0.2%, which is regarded as the systematic error.

Applying a similar method, the efficiency difference of the $\rho^0$ kinematic fit used for vetoing events in the decay $J/\psi \rightarrow D^0 \bar{K}^0$ is determined to be 1.0% using a sample of $J/\psi \rightarrow K^0_S (K^0 \rightarrow K^- \pi^+, K^0_S \rightarrow \pi^+ \pi^-)$ events.

(v) Mass window requirements: The systematic errors of the mass window requirements are due to the difference in mass resolution between MC simulation and data and are estimated from some control samples, which are selected without the mass window requirements. The uncertainty is obtained by comparing the efficiencies of mass window requirements between data and MC events. The uncertainties of $\phi$, $\rho^-$, and $\bar{K}^0$ mass window requirements are 1.0%, 1.0%, 0.5% using samples of $J/\psi \rightarrow \gamma \phi (\phi \rightarrow K^+ K^-$), $J/\psi \rightarrow \rho^+ \pi^-$, and $J/\psi \rightarrow \bar{K}^0 K^0_S$, respectively.

(vi) $U_{miss}$ requirement: The systematic error of the $U_{miss}$ window requirement is due to the mass resolution difference between MC simulation and data. Using a similar method as that used for the mass window requirement, the uncertainties of the $U_{miss}$ requirements are 1.0% for $J/\psi \rightarrow D^+ \rho^+$ and 4.0% for $J/\psi \rightarrow \bar{D}^0 \bar{K}^0$, which are different for the two channels since the $U_{miss}$ requirements are different in these two channels.

(vii) Intermediate decays: The errors on the intermediate-decay branching fractions of $D_s^+ \rightarrow \phi e^- \bar{\nu}_e$, $\phi \rightarrow K^+ K^-$, $\rho^+ \rightarrow \pi^+ \pi^0$, $\rho^0 \rightarrow \gamma \gamma$, and $D^0 \rightarrow K^- e^- \bar{\nu}_e$, $\bar{K}^0 \rightarrow K^- \pi^+$ are taken from world average values [19], and by adding them in quadrature, 5.7% and 1.1% are the errors for $J/\psi \rightarrow D_s^+ \rho^+$ and $J/\psi \rightarrow \bar{D}^0 \bar{K}^0$, respectively.

The systematic error contributions studied above, the error due to the uncertainty on the number of $J/\psi$ events [13], and MC statistics are all summarized in Table I. The total systematic errors are obtained by summing them in quadrature, assuming that they are independent.

### V. RESULTS

No excess of $J/\psi \rightarrow D_s^+ \rho^+$ or $J/\psi \rightarrow \bar{D}^0 \bar{K}^0$ events above background is observed. The upper limits on the

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**TABLE I.** Summary of systematic errors (%).

<table>
<thead>
<tr>
<th>Sources</th>
<th>$J/\psi \rightarrow D_s^+ \rho^+$</th>
<th>$J/\psi \rightarrow \bar{D}^0 \bar{K}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDC tracking</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Photon detection</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle ID</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$\pi^0$ kinematic fit</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>$\phi$ mass window</td>
<td>1.0</td>
<td>...</td>
</tr>
<tr>
<td>$\rho^+$ mass window</td>
<td>1.0</td>
<td>...</td>
</tr>
<tr>
<td>$\bar{K}^0$ mass window</td>
<td>...</td>
<td>0.5</td>
</tr>
<tr>
<td>$U_{miss}$ window</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Intermediate decays</td>
<td>5.7</td>
<td>1.1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Number of $J/\psi$ events</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>8.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

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**TABLE II.** Numbers used in the calculation of upper limits on the branching fractions of $J/\psi \rightarrow D_s^+ \rho^+$ and $J/\psi \rightarrow \bar{D}^0 \bar{K}^0$. $\epsilon$ is the detection efficiency. $B_{inter}$ is the intermediate branching fraction. $\sigma^{sys}$ is the systematic error. $N_{UL}$ is the upper limit of the number of observed events at the 90% C.L. $B$ is the upper limit at the 90% C.L. on the branching fraction.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Intermediate decay</th>
<th>$\epsilon$</th>
<th>$B_{inter}$</th>
<th>$\sigma^{sys}$</th>
<th>$N_{UL}$</th>
<th>$B$ (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow D_s^+ \rho^+$</td>
<td>$D_s^+ \rightarrow \phi e^- \bar{\nu}_e$, $\phi \rightarrow K^+ K^-$, $\rho^+ \rightarrow \pi^+ \pi^0$, $\rho^0 \rightarrow \gamma \gamma$</td>
<td>7.79%</td>
<td>1.20%</td>
<td>8.6%</td>
<td>2.5</td>
<td>&lt; 1.3 × 10^{-5}</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \bar{D}^0 \bar{K}^0$</td>
<td>$\bar{D}^0 \rightarrow K^- e^- \bar{\nu}_e$, $\bar{K}^0 \rightarrow K^- \pi^+$</td>
<td>21.83%</td>
<td>2.37%</td>
<td>7.5%</td>
<td>2.7</td>
<td>&lt; 2.5 × 10^{-6}</td>
</tr>
</tbody>
</table>
branching fractions of these decay modes are calculated using

\[ B < \frac{N_{UL}}{N_{J/\psi^{\prime}} \epsilon B_{\text{inter}} (1 - \sigma_{\text{sys}})}, \]

where \( N_{UL} \) is the upper limit of the number of observed events at the 90\% C.L., \( N_{J/\psi^{\prime}} \) is the number of \( J/\psi \) events, \( \epsilon \) is the detection efficiency, \( B_{\text{inter}} \) is the intermediate branching fraction, and \( \sigma_{\text{sys}} \) is the systematic error.

The upper limits for the observed number of events at the 90\% C.L. are 2.5 for \( J/\psi \to D_{s}^{+} \rho^{+} \) and 2.7 for \( J/\psi \to D^{0} \bar{K}^{0} \) using a series of unbinned extended maximum likelihood fits. In the fit, the recoil mass distributions of data, shown in Fig. 5, are fitted with a probability density function (p.d.f.) signal shape determined from MC simulations, and the background is represented by a second-order Chebychev polynomial. The likelihood distribution, determined by varying the number of signal events from zero to a large number, is taken as the p.d.f. \( N_{UL} \) is the number of events corresponding to 90\% of the integral of the p.d.f. The fit-related uncertainties are estimated by using different fit ranges and different orders of the background polynomial, and \( N_{UL} \) is taken as maximum value among the variations. All numbers used in the calculations of the upper limits on the branching fractions are shown in Table II.

In summary, a search for the weak decays of \( J/\psi \to D_{s}^{+} \rho^{+} \) and \( J/\psi \to D^{0} \bar{K}^{0} \) has been performed using a sample of \( (225.3 \pm 2.8) \times 10^{6} \) \( J/\psi \) events collected at the BESIII detector. No evident signal is observed, and upper limits at the 90\% C.L. are set on the branching fractions, \( B(J/\psi \to D_{s}^{+} \rho^{+}) < 1.3 \times 10^{-5} \) and \( B(J/\psi \to D^{0} \bar{K}^{0}) < 2.5 \times 10^{-6} \), for the first time. These upper limits exclude new physics predictions which allow flavor-changing processes to occur with branching fractions around \( 10^{-5} \) but are still consistent with the predictions of the SM.

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[4] The charge conjugate states are implicitly included throughout this paper.
Throughout this paper, the plot shows the distribution with requirements applied to all other variables except the one shown on it.
