Doubly cabibbo-suppressed $D$ decays at BESIII

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BESIII reports the first observation of the doubly Cabibbo-Suppressed decay $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ and the first evidence for $D^+ \rightarrow K^+\omega$ using an $e^+e^-$ collision data sample corresponding to an integrated luminosity of 2.93 fb$^{-1}$ taken at a center-of-mass energy of 3.773 GeV. The ratio of the branching fractions of $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ over $D^+ \rightarrow K^-\pi^+\pi^-\pi^0$ is significantly larger than other doubly Cabibbo-Suppressed decays in the charm sector. The $CP$ asymmetry in the separated charge-conjugate branching fractions for $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ is determined and no evidence of $CP$ violation is found. An independent measurement of $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ with semileptonic tags is also reported.

Keywords: Charm physics; Hadronic decays; $CP$ violation; Branching fractions; BESIII.

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1. Introduction

Doubly Cabibbo-suppressed (DCS) decays in charm sector play an important role in the understanding of the weak decay mechanisms of charmed hadrons. Compared with the Cabibbo-favored (CF) and singly Cabibbo-suppressed (SCS) decays, the branching fraction (BF) of the DCS decay is expected to be much smaller and only fewer DCS decays have been observed to date [1]. The ratio of DCS to its relative CF counterpart BFs is simply expected to be of the order $\tan^6\theta_C \sim 0.29\%$ [2, 3], where $\theta_C$ is the Cabibbo mixing angle [1]. This expectation is roughly supported by the known rates of DCS and CF decays [1]. Precise measurement of the BF of $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ and the rate with its CF counterpart can offer a crucial check of this expectation.

Measurements of the BFs of $D \rightarrow VP$ decays ($V$ and $P$ refer to vector and pseudoscalar mesons, respectively) provide insight into quark SU(3)-flavor symmetry and charge-parity ($CP$) violation [3–8]. Study of the DCS decay $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ offers an ideal opportunity to determine the BF of $D^+ \rightarrow K^+\omega$. The result is important to improve the understanding of quark SU(3)-flavor symmetry and symmetry breaking, and also benefits theoretical calculations of $CP$ violation [3–8].

In the Standard Model (SM), the direct $CP$ violation is predicted in $D$ decays, e.g., due to a single irreducible phase in the Cabibbo-Kobayashi-Maskawa matrix [9]. In the charm sector, $CP$ violation for SCS processes is expected to be small ($\sim 10^{-3}$), and much smaller for CF and DCS processes [7, 10]. Searching for $CP$ violation in DCS decays allows for more comprehensive understanding of $CP$ violation in the $D$ sector.

BESIII has collected 2.93 fb$^{-1}$ of $e^+e^-$ collision data at the center-of-mass energy of 3.773 GeV. This data sample provides the world largest threshold $D\bar{D}$ sample and an ideal experimental platform to study the DCS decays. Simulated samples produced with the GEANT4-based [11] Monte Carlo (MC) package which includes the geometric description of the BESIII detector and the detector response. The MC samples are generally used in the charm physics of BESIII [12, 13].

2. Measurements of $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$

Taking the advantage of the pair production of $D\bar{D}$ from the data sample, the DCS decay can be studied with the double-tag (DT) technique. Events where one $D^-$ meson is fully reconstructed are referred to as “single-tag” (ST) candidates. A correct tag guarantees the presence of the other $D^+$ meson, and we search for the signal decays recoiling against a tagged $D^-$ meson. Events with both a tag and such a signal-mode candidate are referred to as “double-tag” (DT) events. In this article, we report two methods to measure the BF of $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$. Charge-conjugated decays are always implied except when discussing $CP$ violation.

2.1. Hadronic tags

Hadronic decays are the dominant decay channels of $D^-$ meson [1] and widely used as the tagged channels in $D$ physics [12, 13]. In the first method, the ST $D^-$ meson is reconstructed in one of the three hadronic decay modes $D^- \rightarrow K^-\pi^+\pi^-$, $D^- \rightarrow K^0\pi^-$, and $D^- \rightarrow K^+\pi^-\pi^-\pi^0$. The BF of the signal decay is determined according to

$$B_{\text{sig}} = \frac{N_{\text{DT}}}{N_{\text{ST}}\epsilon_{\text{sig}}\epsilon_{\text{sub}}},$$

where $N_{\text{ST}}$, $N_{\text{DT}}$, $\epsilon_{\text{sig}}$, and $\epsilon_{\text{sub}}$ are the ST yield, DT yield, average efficiency of reconstructing the signal decay, and the BF of $\pi^0 \rightarrow \gamma\gamma$ [1], respectively. $\epsilon_{\text{sig}}$ is weighted by the measured yields of tag modes $i$ in data which is given by

$$\epsilon_{\text{sig}} = \frac{\sum_{i=1}^{3} N_{\text{ST}}^i \epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i}{\sum_{i=1}^{3} N_{\text{ST}}^i}.$$
The ST yields are obtained from maximum likelihood fits to the $M_{BC}^{\text{tag}}$ distributions of the accepted ST candidates [12, 13], where the $M_{BC}^{\text{tag}}$ is defined by

$$M_{BC}^{\text{tag}} = \sqrt{E_b^2 - |\vec{p}_{D^-}|^2},$$

where $E_b$ and $\vec{p}_{D^-}$ are the beam energy and the momentum of $D^-$ candidate in the $e^+e^-$ rest frame. The fit results are shown in Fig. 1. The total ST $D^-$ yield is $N_{ST} = (1150.3 \pm 1.5) \times 10^3$.

The signal $D^+$ candidates are identified using the $M_{BC}$ distribution of the signal side. The dominant peaking background from the singly Cabibbo-Suppressed decay $D^+ \to K^0_SK^+\pi^0$ has been rejected by requiring $|M_{\pi\pi}| > 20$ MeV/$c^2$. Figure 2 shows the comparison of two-body and three-body invariant mass distributions for the $D^+ \to K^+\pi^+\pi^−\pi^0$ candidate events.

Figure 3 shows the comparison of the $M_{\pi\pi\pi^0}$ distributions between data and MC simulation. The signal peak of $D^+ \to K^+\eta$ is clearly seen in Fig. 3. Since the $D^+ \to K^+\eta$ has been well measured by BESIII and $439 \pm 72$ signal events are observed, where $\eta$ is reconstructed by $\gamma\gamma$ and ST method is used [14], we do not report $D^+ \to K^+\eta$ in this article. The definitions of the $\omega$ signal and sideband regions are shown in Fig. 3.

The left column of Fig. 4 shows the distributions of $M_{BC}^{\text{tag}}$ vs. $M_{BC}^{\text{sig}}$ for DT candidate events in data. Signal events and three categories of backgrounds are discussed below:

- Signal events concentrate around $M_{BC}^{\text{tag}} = M_{BC}^{\text{sig}} = M_{D^+}$, where $M_{D^+}$ is the nominal mass of the $D^+$ meson [1].
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Figure 4. Distributions of (left column) $M^{\text{tag}}_{\text{BC}}$ vs. $M^{\text{sig}}_{\text{BC}}$, and the projections of the corresponding 2D fits on (middle column) $M^{\text{tag}}_{\text{BC}}$ and (right column) $M^{\text{sig}}_{\text{BC}}$, for the DT candidate events of $D^- \rightarrow$ all tags vs. $D^+ \rightarrow K^+\pi^+\pi^−\pi^0$. The top, middle, and bottom rows correspond to all events, events lying in $\omega$ signal region, and those falling in $\omega$ sideband region, respectively. In the figures of the middle and right columns, data are shown as dots with error bars; the blue solid, black dashed, blue dot-dashed, red dot-long-dashed, and green dashed curves denote the overall fit results, signal, BKGI, BKGII, and peaking background components, respectively.

- BKGI is from the events with one $D^{+/-}$ meson reconstructed correctly and another $D^{+/-}$ meson reconstructed incorrectly, which distributed along the horizontal and vertical bands.
- BKGII is mainly from the $e^+e^- \rightarrow q\bar{q}$ processes and the events found along the diagonal.
- BKGIII is the events in which both the two $D$ mesons are reconstructed incorrectly.

Peaking backgrounds in the decay $D^+ \rightarrow K^+\pi^+\pi^−\pi^0$ is from $D^+ \rightarrow K^+K^-(\rightarrow \pi^−\pi^0)\pi^+$ decays and from the residual $D^+ \rightarrow K^0_S(\rightarrow \pi^+\pi^-)K^+\pi^0$ events, which are evaluated using the MC simulations. For the decay $D^+ \rightarrow K^+\omega$, the peaking background contributions are dominated by the non-$\omega$ decays $D^+ \rightarrow K^+\pi^+\pi^−\pi^0$.

The DT yields are determined by performing a two-dimensional (2D) unbinned maximum likelihood fit on the corresponding $M^{\text{tag}}_{\text{BC}}$ vs. $M^{\text{sig}}_{\text{BC}}$ distribution. For the decay $D^+ \rightarrow K^+\omega$, simultaneous 2D fits are performed on the events in the $\omega$ signal and sideband regions.

The fit results as well as the BFs are summarized in Table I, and the projections on $M^{\text{tag}}_{\text{BC}}$ and $M^{\text{sig}}_{\text{BC}}$ of the 2D fits to data are shown in the middle and right columns in Fig. 4. The statistical significance of $D^+ \rightarrow K^+\pi^+\pi^−\pi^0$ and $D^+ \rightarrow K^+\omega$ are found to be 23.3σ and 3.3σ, respectively.

Using the world averaged BF for $D^+ \rightarrow K^−\pi^+\pi^+\pi^0$ [1], we determine the ratio of $B_{D^+ \rightarrow K^+\pi^+\pi^−\pi^0}$ over $B_{D^+ \rightarrow K^−\pi^+\pi^+\pi^0}$ to be $(1.81 \pm 0.15)\%$, corresponding to $(6.28 \pm 0.52)\tan^4\theta_C$, which is significantly larger than the values (0.21-0.58)\% for the other DCS decays [1]. This unexpected ratio implies that there may be a massive isospin symmetry violation in the decays $D^+ \rightarrow K^+\pi^+\pi^−\pi^0$ and $D^0 \rightarrow K^+\pi^−\pi^+\pi^0$, which may be caused by final state interactions and very different resonance structures in these two decays.

The BF for the decay $D^+ \rightarrow K^+\omega$ is consistent with theoretical predictions that incorporate quark SU(3)-flavor sym-
of the charge-conjugated decays violation in the charm sector \[3–9\].

CP breaking \[5\] and predictions based on the pole model \[16\] but disfavors predictions in data.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>(N_{ST} (\times 10^3))</th>
<th>(N_{DT})</th>
<th>(\epsilon_{\text{sig}}(%))</th>
<th>(B_{\text{sig}} \times 10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^+ \to K^+\pi^+\pi^-\pi^0)</td>
<td>1150.3 (\pm) 1.5</td>
<td>350 (\pm) 22</td>
<td>25.03 (\pm) 0.13</td>
<td>1.21 (\pm) 0.08 (\pm) 0.03</td>
</tr>
<tr>
<td>(D^\pm \to K^\pm\omega)</td>
<td>1150.3 (\pm) 1.5</td>
<td>9.2 (\pm) 1.0 (\pm) 3.4</td>
<td>14.14 (\pm) 0.09</td>
<td>((5.7 \pm 2.5 \pm 0.2) \times 10^{-2})</td>
</tr>
<tr>
<td>(D^+ \to K^+\pi^+\pi^-\pi^0)</td>
<td>573.5 (\pm) 1.0</td>
<td>181 (\pm) 15</td>
<td>25.20 (\pm) 0.18</td>
<td>1.25 (\pm) 0.11 (\pm) 0.03</td>
</tr>
<tr>
<td>(D^- \to K^-\pi^-\pi^+\pi^0)</td>
<td>572.7 (\pm) 1.0</td>
<td>165 (\pm) 15</td>
<td>24.95 (\pm) 0.18</td>
<td>1.16 (\pm) 0.11 (\pm) 0.03</td>
</tr>
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</table>

The CP asymmetry of \(D^+ \to K^+\pi^+\pi^-\pi^0\) is determined by

\[
A_{CP}^{D^+ \to K^+\pi^+\pi^-\pi^0} = \frac{B_{D^+ \to K^+\pi^+\pi^-\pi^0} - B_{D^- \to K^-\pi^-\pi^+\pi^0}}{B_{D^+ \to K^+\pi^+\pi^-\pi^0} + B_{D^- \to K^-\pi^-\pi^+\pi^0}},
\]

where \(B_{D^+ \to K^+\pi^+\pi^-\pi^0}\) and \(B_{D^- \to K^-\pi^-\pi^+\pi^0}\) are the BFs of the charge-conjugated decays \(D^+ \to K^+\pi^+\pi^-\pi^0\) and \(D^- \to K^-\pi^-\pi^+\pi^0\), which are measured separately. The last two rows of Table I summarize the corresponding ST yields, DT yields, signal efficiencies, and the obtained BFs. The \(A_{CP}^{D^+ \to K^+\pi^+\pi^-\pi^0}\) is determined to be \((-0.04 \pm 0.06_{\text{stat}} \pm 0.01_{\text{syst}}\) after considering the correlated systematic uncertainties of tracking and PID of the \(\pi^+\pi^-\) pair, \(\pi^0\) reconstruction, quoted BFs, and MC modeling. No evidence for CP violation is found.

2.2. Semileptonic tags

In the measurements of DCS \(D^0\) decays using \(e^+e^-\) collision data taken at the \(\psi(3770)\) resonance peak, hadronic tagged method suffers from complicated cross feeds between the events of CF \(D^0\) to tag vs. DCS \(D^0\) to signal and those from DCS \(D^0\) to tag vs. CF \(D^0\) to signal. This is mainly due to there is possible interference between the DCS and CF amplitudes for hadronic neutral \(D\) decays. We introduce and utilize a method using semileptonic \(D^- \to K^0e^-\nu_e\) and \(D^- \to K^+\pi^-e^-\nu_e\) decays to tag the DCS \(D\) decays. This new technique helps to avoid the aforementioned troubles because the semileptonic \(D^0\) decays have no DCS component and the \(D^0 - D^-\) mixing \([17, 18]\) effect is small.

For each of the two semileptonic tags, the BF for \(D^+ \to K^+\pi^+\pi^-\pi^0\) can be determined by

\[
B_{\text{sig}} = \frac{N_{\text{SL, sig}}}{2 \cdot N_{D^+D^-} \cdot B_{\text{SL}} \cdot \epsilon_{\text{SL, sig}} \cdot B_{\text{sub}}},
\]

where \(N_{\text{SL, sig}}\) is the yield of the signal DT events in the data sample, \(N_{D^+D^-} = (8296 \pm 31 \pm 65) \times 10^3\) is the total number of \(D^+D^-\) pairs \([19]\), \(B_{\text{SL}}\) is the BF for the semileptonic decay \([1]\), \(\epsilon_{\text{SL, sig}}\) is the efficiency of reconstructing the DT.
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events, $B_{sub}$ is the BFs $B_{\pi^0 \rightarrow \gamma \gamma}$ and $B_{K^0 \rightarrow \pi^+ \pi^-}$. Throughout this section, charge conjugate modes are implied. Information concerning the undetectable neutrino is inferred by the kinematic quantity defined as

$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2,$$

where $E_{\text{miss}}$ and $\vec{p}_{\text{miss}}$ are the missing energy and momentum of the DT event in the $e^+e^-$ center-of-mass system.

The distributions of $M_{BC}$ vs. $M^2_{\text{miss}}$ for the DT candidates in data are shown in Fig. 5. The signal DT candidate events concentrate around the $D^+$ known mass and zero.

The signal yield is extracted by the unbinned maximum likelihood simultaneous fits on the $M^2_{\text{miss}}$ distributions for the two semileptonic tags. In the fit, the two semileptonic tags are constrained to have the same BF for $D^+ \rightarrow K^+ \pi^+ \pi^+ \pi^0$. The fit results are shown in Fig. 6. The fits give a total yield of $112 \pm 12$ for signal DT events. Using the signal MC events, the efficiencies of reconstructing the DT events $D^- \rightarrow K^0 e^- \bar{\nu}_e$ and $D^- \rightarrow K^+ e^- \bar{\nu}_e$ are obtained to be $0.103 \pm 0.001$ and $0.076 \pm 0.001$, respectively, where the efficiencies do not include the BFs for $K^0 \rightarrow \pi^+ \pi^-$ and $\pi^0 \rightarrow \gamma \gamma$. The BF is determined to be $B(D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0) = (1.03 \pm 0.12 \pm 0.06) \times 10^{-3}$ after subtracting the sum of the product BFs for decays containing narrow intermediate resonances, $D^+ \rightarrow K^+ X (X = \eta, \omega, \phi)$ with $X \rightarrow \pi^+ \pi^- \pi^0$. This result is consistent with the one tagged by hadronic tags.

2.3. Combined results

After considering the correlated uncertainties of $K^{\pm}$, $\pi^+ \pi^-$ tracking and PID, $\pi^0$ reconstruction, and MC model, the averaged BFs of $D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0$ measured by two tagged methods are determined to be $B_{D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0} = (1.10 \pm 0.07 \pm 0.03)\%$. The ratio of $B_{D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0}/B_{D^+ \rightarrow K^- \pi^+ \pi^- \pi^0}$ is determined to be $(1.76 \pm 0.13)\%$, corresponding to $(6.11 \pm 0.52)\tan^4 \theta_C$.

3. Summary and Outlook

BESIII reports the first observation of the DCS decay $D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0$ and the first evidence for $D^+ \rightarrow K^+ \omega$. The BF of $D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0$ is the largest among the known DCS $D$ decays. The ratio of $B_{D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0}/B_{D^+ \rightarrow K^- \pi^+ \pi^- \pi^0}$ is determined to be $(6.11 \pm 0.52)\tan^4 \theta_C$, which is significantly larger than the values $(0.21-0.58)\%$ for the other DCS decays in charm sector. No evidence for $CP$ violation is found in $D^\pm \rightarrow K^{\pm} \pi^+ \pi^- \pi^0$.

In the near future, BESIII plan to collect another 17 $fb^{-1}$ $e^+e^-$ collision data sample at $\sqrt{s} = 3.773$ GeV [20]. With larger data samples, amplitude analyses of this decay will provide crucial information for understanding the origin of the anomalously large ratio. Meanwhile, more other DCS decays, $D^+ \rightarrow K^+ \eta$, $D^0 \rightarrow K^+ \pi^- \bar{\eta}$, $D^+ \rightarrow K^+ \eta \bar{\eta}$, etc., will also be studied and help to check the theoretical prediction [3,5].
This contribution is calculated by \[ \sum_{R=1}^{3} \left[ B(D^+ \to K^+ R) \cdot B(R \to \pi^+ \pi^- \pi^0) \right] \], where \( R \) sums over \( \eta, \omega, \) and \( \phi \), \( B(D^+ \to K^+ \omega) \) is obtained in this work, and the other BFs are quoted from the PDG [1].