

Search for CP violation in D decays to radiative and hadronic decays and search for rare D decay at Belle

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Using the large data sample accumulated by the Belle experiment at KEKB asymmetry energy e^+e^- Collider, we report the preliminary measurements of the branching fractions of the radiative decays $D^0 \rightarrow V\gamma$, where $V = \phi, \bar{K}^{*0}, \rho^0$. This is the first observation of the decay $D^0 \rightarrow \rho^0\gamma$ and also present the preliminary results of the first measurement of CP asymmetry in these decays. We present the preliminary result of the CP asymmetry of the $D^0 \rightarrow K_S^0 K_S^0$ decay, which is consistent with no CP violation and improves the uncertainty with respect to the previous measurement of this quantity by more than a factor of three. Finally, we present the results of the rare charm decay $D^0 \rightarrow \gamma\gamma$, resulting in the most restrictive upper limit to date.

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1. Introduction

Charge-conjugation Parity Violation (CPV) in charmed meson decays has not yet been observed and is predicted in the Standard Model (SM) to be small (10^{-3}). An evidence for CPV in 2012 by LHCb ($-0.82 \pm 0.21 \pm 0.11\%$) [1] suggested a 3.5 standard deviation (σ), confirmed by CDF [2], took people by surprise and revived the field. Measurements of ΔA_{CP} ($A_{CP}^{D^0 \rightarrow \pi^+ \pi^-} - A_{CP}^{D^0 \rightarrow K^+ K^-}$) have been performed by LHCb, CDF, BaBar and Belle collaborations [3]- [4]. Recently LHCb updated ΔA_{CP} result with a larger data sample and there is no evidence of non-zero asymmetry [4]. The combined result of ΔA_{CP} by HFAG [5] gives an agreement with no CP violation at 6.5% CL. Though there is no current evidence of non-zero asymmetry, CPV in charm decays is investigated in other channels. It is interesting to measure CPV in D^0 decays to neutral final states such as $V\gamma$ ($V = \phi, \bar{K}^{*0}, \rho^0$), $K_S^0 K_S^0$. This report also presents a search for the rare charm decay $D^0 \rightarrow \gamma\gamma$, which has not been observed yet.

The D^0 candidates are selected as coming from the decay $D^{*+} \rightarrow D^0 \pi_s^+$, where π_s^+ denotes the low-momentum "slow" pion. The charge of this slow pion reveals the flavor content of neutral D meson (whether it is a D^0 or \bar{D}^0) at its production vertex [6]. A stringent selection criterion is applied on the momentum of the D^{*+} candidate in the e^+e^- center-of-mass frame, $p^*(D^*)$, to suppress D^{*+} coming from B decays as well as to reduce the combinatorial background. The D^{*+} mesons mostly originate from the $e^+e^- \rightarrow c\bar{c}$ process via hadronization, where the inclusive yield has a large uncertainty of 12.5% [7]. To avoid this uncertainty, we measure the branching fraction of signal decay mode with respect to the well measured mode as a normalization decay using the following relation: $\mathcal{B}_{sig} = \mathcal{B}_{norm} \times \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}$, where N is the extracted yield, ϵ the reconstructed efficiency and \mathcal{B} the branching fraction for signal and normalization modes, respectively. For \mathcal{B}_{norm} , the world average value [7] is used. Assuming the total decay width to be same for particles and antiparticles, the time-integrated A_{CP} is given as:

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})} \quad (1.1)$$

where, Γ represents the partial decay width and f is specific final state. The extracted raw asymmetry is given by:

$$A_{raw} = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow \bar{f})}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow \bar{f})} = A_{CP} + A_{FB} + A_{\epsilon}^{\pm} \quad (1.2)$$

Here, A_{FB} is the forward-backward production asymmetry, and A_{ϵ}^{\pm} is the asymmetry due to different detection efficiencies for positively and negatively charged pions. Both can be eliminated through a relative measurement of A_{CP} if the charged final-state particles are identical. The CP asymmetry of the signal mode can then be expressed as: $A_{CP}(sig) = A_{raw}(sig) - A_{raw}(norm) + A_{CP}(norm)$. For $A_{CP}(norm)$, the world average value [7] is used. Both the branching fraction and A_{CP} are measured relative to other well measured decay channels. Such an approach enables the cancellation of several sources of systematic uncertainties that are common to both the signal and normalisation mode. All the analysis results presented here are based on data collected by the Belle detector, operating at the asymmetric KEKB e^+e^- collider [8].

2. Search for radiative and hadronic decays $D^0 \rightarrow V\gamma$

The radiative charm decay, $D^0 \rightarrow \phi\gamma$ has been first observed by the Belle Collaboration [9]. In a subsequent analysis, the BaBar Collaboration measured both the decay, $D^0 \rightarrow \phi\gamma$ and $D^0 \rightarrow \bar{K}^{*0}\gamma$ [10]. The current world average values of the branching fractions are $(2.70 \pm 0.35) \times 10^{-5}$ (ϕ mode) and $(32.7 \pm 3.4) \times 10^{-5}$ (\bar{K}^{*0} mode) [11]. The decay, $D^0 \rightarrow \rho^0\gamma$ has not been observed up to date; the established upper limit by CLEO II is $\mathcal{B}(D^0 \rightarrow \rho^0\gamma) < 24 \times 10^{-5}$ at 90% confidence level [12]. As radiative charm decays are dominated by non-perturbative long range dynamics, measurements of branching fractions can be a useful test for the QCD based theoretical calculations of the branching fractions. Further motivation for a study of radiative decays $D^0 \rightarrow V\gamma$, where V is a vector meson, is that these decays could be sensitive to New Physics (NP) via CP asymmetry (A_{CP}). Theoretical studies [13] [14] predict that in the SM extensions with chromomagnetic dipole operators, A_{CP} can rise to several percent for $V = \phi, \rho^0$, compared to the $\mathcal{O}(10^{-3})$ SM expectation. However, there has been no study of CP violation in $D^0 \rightarrow V\gamma$ decays conducted up to this point. The preliminary results of the measurement of the branching fractions and CP asymmetries in decays $D^0 \rightarrow V\gamma$ are presented here, where $V = \phi, \bar{K}^{*0}, \rho^0$. This is the first observation of the decay $D^0 \rightarrow \rho^0\gamma$. The analysis is based on 943 fb^{-1} of data collected by the Belle detector, operating at the asymmetric KEKB e^+e^- collider [15]. The chosen normalisation modes are decays that feature the same charged final state particles as the signal decay. The signal decays are reconstructed in the following sub-decay channels of the vector meson: $\phi \rightarrow K^+K^-$, $\bar{K}^{*0} \rightarrow K^-\pi^+$ and $\rho^0 \rightarrow \pi^+\pi^-$. In accordance, the corresponding normalisation modes are $D^0 \rightarrow K^+K^-$ (ϕ mode), $D^0 \rightarrow K^-\pi^+$ (\bar{K}^{*0} mode) and $D^0 \rightarrow \pi^+\pi^-$ (ρ^0 mode).

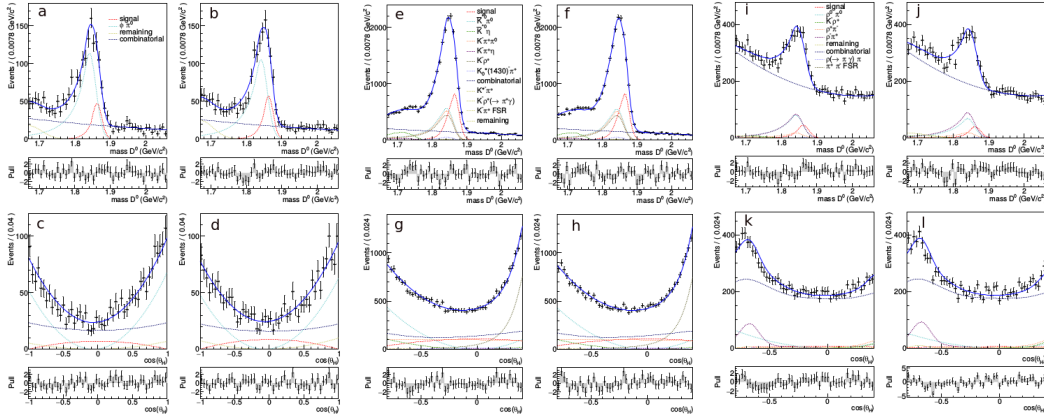


Figure 1: The $M(D^0)$ (top row) and $\cos\theta_H$ (bottom row) distributions for (a-d) the ϕ mode, (e-h) the \bar{K}^{*0} mode and (i-l) the ρ^0 mode, in each D^0 (left) and \bar{D}^0 (right), with fit results superimposed.

2.1 Signal extraction and Systematic uncertainties

Signal is extracted via a simultaneous 2-dimensional fit in the variables $m(D^0)$ and the cosine of the helicity angle ($\cos\theta_H$), defined as the angle between the D^0 and positively (or negatively) charged hadron in the rest frame of the V meson. The background arises from decays π^0 to a

61 pair of photons are suppressed [19]. The fit results are shown in Figure 1 for the ϕ, \bar{K}^{*0} and ρ^0
 62 modes, respectively. The signal component is denoted with the dashed red line. The extracted
 63 signal yields are 524 ± 35 (ϕ mode), 9104 ± 396 (\bar{K}^{*0} mode) and 500 ± 85 (ρ^0 mode). The extracted
 64 raw asymmetries are -0.091 ± 0.066 (ϕ mode), -0.002 ± 0.020 (\bar{K}^{*0} mode) and 0.064 ± 0.151
 65 (ρ^0 mode). Here, the uncertainties are statistical only. The reconstruction efficiencies are 9.7%
 66 (ϕ mode), 7.8% (\bar{K}^{*0} mode) and 6.8% (ρ^0 mode). All the sources of systematic uncertainties are
 67 summarized in Ref. [19].

68 2.2 Results

69 The preliminary results are

$$70 \mathcal{B}(D^0 \rightarrow \phi \gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}, A_{CP}(D^0 \rightarrow \phi \gamma) = -0.094 \pm 0.066 \pm 0.001,$$

$$71 \mathcal{B}(D^0 \rightarrow \bar{K}^{*0} \gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}, A_{CP}(D^0 \rightarrow \bar{K}^{*0} \gamma) = -0.003 \pm 0.020 \pm 0.000,$$

$$72 \mathcal{B}(D^0 \rightarrow \rho^0 \gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}, A_{CP}(D^0 \rightarrow \rho^0 \gamma) = +0.056 \pm 0.151 \pm 0.006$$

73 where the first uncertainty is statistical and the second is systematic. The branching fraction
 74 result of the ϕ mode is improved compared to the previous Belle result and is consistent with the
 75 world average value [7]. The branching fraction of the \bar{K}^{*0} mode reported here is 3.3σ away from
 76 the result of the BaBar analysis. For the ρ^0 mode, this analysis reports the first observation of the
 77 decay. The significance of the observation is greater than 5σ , including systematic uncertainties.
 78 We also report the first-ever measurement of A_{CP} in the decays $D^0 \rightarrow V\gamma$. Results are consistent
 79 with no CP asymmetry in any of the $D^0 \rightarrow V\gamma$ decay modes.

80 3. Search for $D^0 \rightarrow K_S^0 K_S^0$ decay

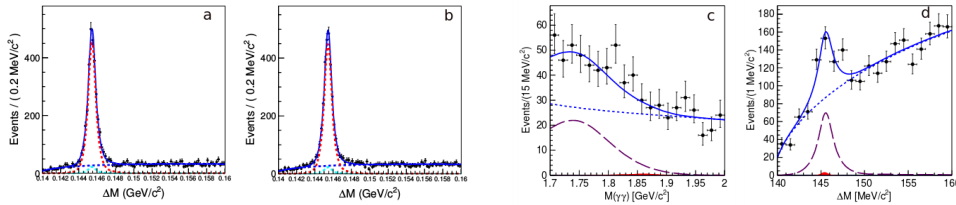


Figure 2: (a,b), Distribution of the mass difference ΔM for the $K_S^0 K_S^0$, left(right) for the D^{*+} (D^{*-}). Points with error bars are the data, the solid curves show the results of the fit, dashed (blue) curves are the background predictions and solid (cyan) is for the peaking background. (c,d), 2-dimensional fit in $M(D^0)$ (left) and ΔM (right). Blue (purple) dashed line denotes the combinatorial (peaking) background, while red histogram shows the signal component for the $D^0 \rightarrow \gamma\gamma$.

81 The $D^0 \rightarrow K_S^0 K_S^0$ decay is Single Cabibbo Suppressed channel [20]. The most recent SM-
 82 based analysis obtained a 95% confidence level upper limit of 1.1% for direct CP violation in this
 83 decay [21]. The search for CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ has been performed first by the CLEO
 84 Collaboration [22] using a data sample of 13.7 fb^{-1} as $(-23 \pm 19)\%$. Recently LHCb measured
 85 time-integrated CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ as $(-2.9 \pm 5.2 \pm 2.2)\%$, where the first uncertainty
 86 is statistical and the second is systematic [23]. The LHCb result is consistent with no CPV, in
 87 agreement with SM expectations. We present here the preliminary result of the measurement of the
 88 CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ decays using 921 fb^{-1} data collected at the Belle detector.

89 3.1 Signal extraction and Systematic uncertainties

90 Signal is extracted via a simultaneous fit of the ΔM , where ΔM is the mass difference between
 91 reconstructed D^* and D^0 . Here the normalization mode is $D^0 \rightarrow K_S^0 \pi^0$. The ΔM distribution for
 92 the signal mode $D^0 \rightarrow K_S^0 K_S^0$ is shown in Figure 2. The signal yield for $D^0 \rightarrow K_S^0 K_S^0$ is $5,399 \pm 87$
 93 events and for $D^0 \rightarrow K_S^0 \pi^0$ is $531,807 \pm 796$ events. A simultaneous fit of the ΔM for D^{*+} and
 94 D^{*-} is used (Figure 2) to estimate the asymmetry. The A_{raw} observed in data for $D^0 \rightarrow K_S^0 K_S^0$ and
 95 $D^0 \rightarrow K_S^0 \pi^0$ decay mode are $(+0.45 \pm 1.53)\%$ and $(+0.16 \pm 0.14)\%$, respectively. We identify
 96 four sources of systematic uncertainty. The first is due to the uncertainties of the signal shapes,
 97 second we correct for a non-vanishing asymmetry originating from the different strong interaction
 98 of K^0 and \bar{K}^0 mesons with nucleons of the detector material, estimated to be -0.11% and assign
 99 an additional systematic uncertainty of 0.01% . Third, the peaking background yield is determined
 100 and fixed from the K_S^0 mass sideband. Fourth, the fit procedure is repeated with its yield varied by
 101 its statistical uncertainty. Similarly, for its raw asymmetry, fixed from the $K_S^0 \pi^0$ measurement. The
 102 total systematic uncertainty for the time integrated CP violating asymmetry A_{CP} in the $D^0 \rightarrow K_S^0 K_S^0$
 103 decay is $\pm 0.17\%$ [25].

104 3.2 Results

105 The measured time-integrated CP-violating asymmetry A_{CP} in the $D^0 \rightarrow K_S^0 K_S^0$ decay is found
 106 to be $A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%$ using a data sample of 921 fb^{-1} integrated luminosity.
 107 The dominant systematic uncertainty comes from the A_{CP} error of the normalisation channel. The
 108 result is consistent with SM expectations and is a significant improvement compared to the previous
 109 measurements of CLEO [22] and LHCb Collaborations [23], already probing the region of interest.

110 4. Search for rare decay $D^0 \rightarrow \gamma\gamma$

111 We also present a search for the rare charm decay $D^0 \rightarrow \gamma\gamma$ [24]. This decay has not been
 112 observed yet. The best upper limit to date was set by BaBar at $\mathcal{B}(D^0 \rightarrow \gamma\gamma) < 2.2 \times 10^{-6}$ (90% C.L.)
 113 [16]. The decay $D^0 \rightarrow \gamma\gamma$ represents a good probe for NP as the SM prediction for the branching
 114 fraction, which is of the order of $\mathcal{O}(10^{-8})$, can be enhanced by several orders of magnitude by NP
 115 contributions. The Minimal Supersymmetric Standard Model suggests that the exchange of gluinos
 116 can enhance the $D^0 \rightarrow \gamma\gamma$ branching ratio up to 6×10^{-6} [17] [18]. The present measurement,
 117 conducted on 832 fb^{-1} of Belle data, represents the most stringent upper limit for this decay.
 118 Peaking background arises from decays comprising a π^0 and/or η meson, which decays to a pair of
 119 photons: $D^0 \rightarrow \pi^0 \pi^0$, $D^0 \rightarrow \eta \pi^0$, $D^0 \rightarrow \eta \eta$, $D^0 \rightarrow K_S^0 (\pi^0 \pi^0) \pi^0$, $D^0 \rightarrow K_L^0 \pi^0$. These background
 120 types are suppressed with a $\pi^0(\eta)$ veto and suppression of merged ECL clusters through the ratio
 121 $\frac{E_9}{E_{25}}$. The branching fraction is calculated relative to the normalisation mode $D^0 \rightarrow K_S^0 \pi^0$.

122 4.1 Signal extraction and Systematic uncertainties

123 Signal is extracted through a 2-dimensional fit of $m(D^0)$ and Δm as shown in the Figure 2. The
 124 efficiency is 7.3% and we extract a signal yield of 4 ± 15 events. The efficiency is 7.2% and we
 125 extract a yield of 343050 ± 673 events for the normalisation channel. The systematic uncertainties
 126 are summarized in Ref. [24].

127 4.2 Results

128 In the absence of signal, a frequentist method is used to estimate the upper limit on the branch-
129 ing fraction at a 90% confidence level. The final result after including systematic uncertainties is
130 $\mathcal{B}(D^0 \rightarrow \gamma\gamma) < 8.4 \times 10^{-7}$ at 90% C.L. [24]. This result represents the world's most stringent
131 upper limit to date.

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