Observation of $D^+ \to K^+\eta^{(\prime)}$ and Search for CP Violation in $D^+ \to \pi^+\eta^{(\prime)}$ Decays

E. Won,[21] B. R. Ko,[21] I. Adachi,[9] H. Aihara,[51] K. Arinstein,[1] D. M. Asner,[38] T. Aushev,[16] A. M. Bakich,[45] E. Barberio,[27] A. Bay,[23] V. Bhardwaj,[39] B. Bhuyan,[11] M. Bischofberger,[29] A. Bondar,[1] A. Bozek,[33] M. Bračko,[25,17] J. Brodzicka,[33] T. E. Browder,[8] P. Chang,[32] A. Chen,[30] P. Chen,[32] B. G. Cheon,[7] K. Chilikin,[16] I.-S. Cho,[56] K. Cho,[20] S.-K. Choi,[6] Y. Choi,[44] J. Dalseno,[26,47] M. Danilov,[16] Z. Doležal,[2] Z. Drásal,[2] A. Drutskoy,[16] S. Eidelman,[1] J. E. Fast,[38] V. Gaur,[46] N. Gabyshev,[1] A. Garmash,[1] Y. M. Goh,[7] B. Golob,[24,17] J. Haba,[9] T. Hara,[9] K. Hayasaka,[28] H. Hayashii,[29] Y. Horii,[50] Y. Hoshi,[49] W.-S. Hou,[32] Y. B. Hsiung,[32] H. J. Hyun,[22] T. Iijima,[28] K. Inami,[28] A. Ishikawa,[50] R. Itoh,[9] M. Iwabuchi,[56] Y. Iwasaki,[9] T. Iwashita,[29] N. J. Joshi,[46] T. Julius,[27] J. H. Kang,[56] N. Katayama,[9] T. Kawasaki,[35] H. Kichimi,[9] H. J. Kim,[22] H. O. Kim,[22] J. B. Kim,[21] J. H. Kim,[20] K. T. Kim,[21] M. J. Kim,[22] S. K. Kim,[43] Y. J. Kim,[20] K. Kinoshita,[3] N. Kobayashi,[40,52] S. Koblitz,[26] P. Kodyš,[2] S. Korpar,[25,17] P. Križan,[24,17] T. Kumita,[53] A. Kuzmin,[1] Y.-J. Kwon,[56] J. S. Lange,[4] M. J. Lee,[43] S.-H. Lee,[21] J. Li,[43] Y. Li,[55] J. Libby,[12] C.-L. Lim,[56] C. Liu,[42] Y. Liu,[32] D. Liventsev,[16] R. Louvot,[23] S. McOnie,[45] K. Miyabayashi,[29] H. Miyata,[35] Y. Miyazaki,[28] R. Mizuk,[16] G. B. Mohanty,[46] Y. Nagasaka,[10] E. Nakano,[37] M. Nakao,[9] H. Nakazawa,[30] Z. Natkaniec,[33] S. Neubauer,[19] S. Nishida,[9] K. Nishimura,[8] O. Nitoh,[54] S. Ogawa,[48] T. Ohshima,[28] S. Okuno,[18] S. L. Olsen,[43,8] Y. Onuki,[50] P. Pakhlov,[16] G. Pakhlova,[16] H. Park,[22] H. K. Park,[22] K. S. Park,[44] R. Pestotnik,[17] M. Petrič,[17] L. E. Piilonen,[55] M. Röhrken,[19] S. Ryu,[43] H. Sahoo,[8] K. Sakai,[9] Y. Sakai,[9] T. Sanuki,[50] O. Schneider,[23] C. Schwanda,[14] A. J. Schwartz,[3] K. Senyo,[28] O. Seon,[28] M. E. Sevior,[27] C. P. Shen,[28] T.-A. Shibata,[40,52] J.-G. Shiu,[32] F. Simon,[26,47] J. B. Singh,[39] P. Smerkol,[17] Y.-S. Sohn,[56] A. Sokolov,[15] E. Solovieva,[16] S. Stanič,[36] M. Starič,[17] M. Sumihama,[40,5] T. Sumiyoshi,[53] S. Suzuki,[41] G. Tatishvili,[38] Y. Teramoto,[37] K. Trabelsi,[9] M. Uchida,[40,52] S. Uehara,[9] T. Uglov,[16] Y. Unno,[7] S. Uno,[9] Y. Usov,[1] S. E. Vahsen,[8] G. Varner,[8] A. Vinokurova,[1] C. H. Wang,[31] M.-Z. Wang,[32] P. Wang,[13] M. Watanabe,[35] Y. Watanabe,[18] K. M. Williams,[55] B. D. Yabsley,[45] Y. Yamashita,[34] M. Yamauchi,[9] Z. P. Zhang,[42] V. Zhilich,[1] V. Zhulanov,[1] A. Zupanc,[19] and O. Zyukova[1]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University, Novosibirsk 630090*
[2]*Faculty of Mathematics and Physics, Charles University, Prague*
[3]*University of Cincinnati, Cincinnati, Ohio 45221*
[4]*Justus-Liebig-Universität Gießen, Gießen*
[5]*Gifu University, Gifu*
[6]*Gyeongsang National University, Chinju*
[7]*Hanyang University, Seoul*
[8]*University of Hawaii, Honolulu, Hawaii 96822*
[9]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[10]*Hiroshima Institute of Technology, Hiroshima*
[11]*Indian Institute of Technology Guwahati, Guwahati*
[12]*Indian Institute of Technology Madras, Madras*
[13]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[14]*Institute of High Energy Physics, Vienna*
[15]*Institute of High Energy Physics, Protvino*
[16]*Institute for Theoretical and Experimental Physics, Moscow*
[17]*J. Stefan Institute, Ljubljana*
[18]*Kanagawa University, Yokohama*
[19]*Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe*
[20]*Korea Institute of Science and Technology Information, Daejeon*
[21]*Korea University, Seoul*
[22]*Kyungpook National University, Taegu*
[23]*École Polytechnique Fédérale de Lausanne (EPFL), Lausanne*
[24]*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*
[25]*University of Maribor, Maribor*
[26]*Max-Planck-Institut für Physik, München*
[27]*University of Melbourne, School of Physics, Victoria 3010*
[28]*Nagoya University, Nagoya*
[29]*Nara Women's University, Nara*
[30]*National Central University, Chung-li*

[31]National United University, Miao Li
[32]Department of Physics, National Taiwan University, Taipei
[33]H. Niewodniczanski Institute of Nuclear Physics, Krakow
[34]Nippon Dental University, Niigata
[35]Niigata University, Niigata
[36]University of Nova Gorica, Nova Gorica
[37]Osaka City University, Osaka
[38]Pacific Northwest National Laboratory, Richland, Washington 99352
[39]Panjab University, Chandigarh
[40]Research Center for Nuclear Physics, Osaka
[41]Saga University, Saga
[42]University of Science and Technology of China, Hefei
[43]Seoul National University, Seoul
[44]Sungkyunkwan University, Suwon
[45]School of Physics, University of Sydney, NSW 2006
[46]Tata Institute of Fundamental Research, Mumbai
[47]Excellence Cluster Universe, Technische Universität München, Garching
[48]Toho University, Funabashi
[49]Tohoku Gakuin University, Tagajo
[50]Tohoku University, Sendai
[51]Department of Physics, University of Tokyo, Tokyo
[52]Tokyo Institute of Technology, Tokyo
[53]Tokyo Metropolitan University, Tokyo
[54]Tokyo University of Agriculture and Technology, Tokyo
[55]CNP, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[56]Yonsei University, Seoul

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We report the first observation of the doubly Cabibbo-suppressed decays $D^+ \to K^+ \eta^{(\prime)}$ using a 791 fb^{-1} data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The ratio of the branching fractions of doubly Cabibbo-suppressed relative to singly Cabibbo-suppressed $D^+ \to \pi^+ \eta^{(\prime)}$ decays are $\mathcal{B}(D^+ \to K^+ \eta)/\mathcal{B}(D^+ \to \pi^+ \eta) = (3.06 \pm 0.43 \pm 0.14)\%$ and $\mathcal{B}(D^+ \to K^+ \eta')/\mathcal{B}(D^+ \to \pi^+ \eta') = (3.77 \pm 0.39 \pm 0.10)\%$. From these, we find that the relative final-state phase difference between the tree and annihilation amplitudes in D^+ decays, $\delta_{\rm TA}$, is $(72 \pm 9)^\circ$ or $(288 \pm 9)^\circ$. We also report the most precise measurements of CP asymmetries to date: $A_{CP}^{D^+ \to \pi^+ \eta} = (+1.74 \pm 1.13 \pm 0.19)\%$ and $A_{CP}^{D^+ \to \pi^+ \eta'} = (-0.12 \pm 1.12 \pm 0.17)\%$.

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Decays of charmed mesons play an important role in understanding the sources of SU(3) flavor symmetry breaking structure [1,2] and can also be sensitive probes of the violation of the combined charge-conjugation and parity symmetries (CP) produced by the irreducible complex phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [3] in the standard model (SM). This SU(3) flavor symmetry structure is not well studied in D^+ meson decays into two-body final states with an $\eta^{(\prime)}$, since they are all Cabibbo-suppressed decays. Examples of two-body decays with an $\eta^{(\prime)}$ in the final state are the doubly Cabibbo-suppressed (DCS) decays $D^+ \to K^+ \eta^{(\prime)}$ and the singly Cabibbo-suppressed (SCS) decays $D^+ \to \pi^+ \eta^{(\prime)}$. The DCS decays $D^+ \to K^+ \eta^{(\prime)}$ have not yet been observed. The observation of such modes is not only intrinsically important to illuminate the meson decay process but also there is general interest in the experimental technique of measuring an extremely rare decay process with neutral particles. Observation of $D^+ \to K^+ \eta^{(\prime)}$ would complete the picture of DCS decays for D^+ mesons decaying to pairs of light pseudoscalar mesons.

In this Letter, we report the first observation of $D^+ \to K^+ \eta^{(\prime)}$ decays. The DCS decays $D^+ \to K^+ \eta^{(\prime)}$ together with $D^+ \to K^+ \pi^0$ can be used to measure the relative phase difference between the tree and annihilation amplitudes ($\delta_{\rm TA}$), which is an important piece of information relevant to final-state interactions in D meson decays. Note that experimentally one is able to determine only the tree and annihilation amplitudes and the relative phase difference between them since all decays involving K^0 will be overwhelmed by Cabibbo-favored decays involving a $\bar{K}^0$, with no way to distinguish between them because one detects only a K_S^0 [4]. In addition, the most sensitive search for CP violation in $D^+ \to \pi^+ \eta^{(\prime)}$ decays is reported. Observation of CP violation in $D^+ \to \pi^+ \eta^{(\prime)}$ decays with current experimental sensitivity would represent strong evidence for processes involving physics beyond the SM [5].

The data used in this analysis were recorded at or near the $\Upsilon(4S)$ resonance with the Belle detector [6] at the e^+e^- asymmetric-energy collider KEKB [7]. The sample corresponds to an integrated luminosity of 791 fb^{-1}.

We apply the same charged track selection criteria that were used in Ref. [8]. Charged kaons and pions are identified by requiring the ratio of particle identification (PID) likelihoods [8] to be greater or less than 0.6, respectively. For kaons (pions) used in this analysis, the efficiencies and misidentification probabilities are approximately 87% (88%) and 9% (10%), respectively. For the reconstruction of the η meson in the $D^+ \to h^+\eta$ decay, where h^+ refers to either π^+ or K^+, we use the $\eta \to \pi^+\pi^-\pi^0$ mode instead of the frequently used $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$) mode since our event selection will include stringent requirements on the vertex formed from charged tracks in the η decay. We find that the $\eta \to \gamma\gamma$ mode has a small signal to background ratio and poor η invariant mass resolution that prohibit the final signal extraction from our data. To reconstruct the η' meson in $D^+ \to h^+\eta'$ decay, we use the $\eta' \to \pi^+\pi^-\eta_{\gamma\gamma}$ decay. The minimum energy of the γ from the π^0 or η is chosen to be 60 MeV for the barrel and 100 MeV for the forward region of the calorimeter [9]. The decay vertex of the D^+ is formed by fitting the three charged tracks ($h^+\pi^+\pi^-$) to a common vertex and requiring a confidence level (C.L.) greater than 0.1%. For π^0 reconstruction in $D^+ \to h^+\eta$, we require the invariant mass of the $\gamma\gamma$ pair to be within [0.12, 0.15] GeV/c^2 and for the η we require the invariant mass of the $\pi^+\pi^-\pi^0$ system to be within [0.538, 0.558] GeV/c^2. In the $D^+ \to h^+\eta'$ mode, to reconstruct the daughter $\eta_{\gamma\gamma}$, we require the invariant mass of the $\gamma\gamma$ pair to be within [0.50, 0.58] GeV/c^2. Furthermore, in order to remove a significant π^0 contribution under the $\eta_{\gamma\gamma}$ signal peak, we reject γ candidates as described in Ref. [10]. The $\pi^+\pi^-\eta_{\gamma\gamma}$ invariant mass is required to be within the range [0.945, 0.970] GeV/c^2. The momenta of photons from the π^0 and the $\eta_{\gamma\gamma}$ combination are recalculated with π^0 and η mass [11] constraints, respectively. The invariant mass distributions of the $h^+\eta^{(\prime)}$ system after the initial selection described above are shown in Fig. 1 where there is little indication of signal for either of the DCS modes.

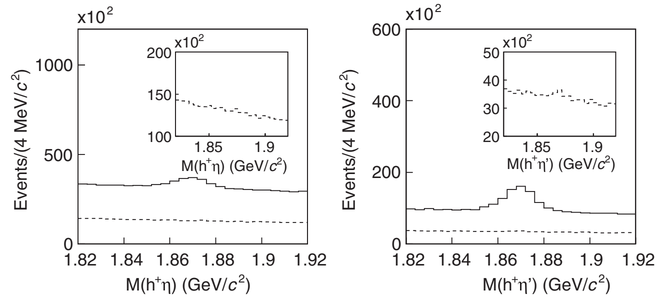

FIG. 1. The invariant mass distributions of $h^+\eta$ ($h^+\eta'$) in the left (right) plot after the initial selection. The solid histograms show $\pi^+\eta^{(\prime)}$ while the dashed histograms show $K^+\eta^{(\prime)}$ final states. The two inset histograms are $K^+\eta^{(\prime)}$ decays with enlarged vertical scales.

In order to search for $D^+ \to K^+\eta^{(\prime)}$ decays, the following four variables are considered. The first is the angle (ξ) between the charmed meson momentum vector, as reconstructed from the daughter particles, and the vector joining its production and decay vertices [12]. The second variable is the isolation χ^2 (χ^2_{iso}) normalized by the number of degrees of freedom (d.o.f.) for the hypothesis that the candidate tracks forming the charmed meson arise from the primary vertex, where the primary vertex is the most probable point of intersection of the charmed meson momentum vector and the e^+e^- interaction region [12]. Because of the finite lifetime of D^+ mesons their daughter tracks are not likely to be compatible with the primary vertex. The third and the fourth variables are the momentum of the $\eta^{(\prime)}$ ($p_{\eta^{(\prime)}}$) in the laboratory system, and the momentum of the D^+ in the center-of-mass system ($p^*_{D^+}$). To optimize the selection, we maximize $\epsilon_{\text{sig}}/\sqrt{\mathcal{N}_B}$ where ϵ_{sig} and $\mathcal{N}_B$ are the signal efficiency and the background yield in the invariant mass distribution of D^+ candidates. A uniform grid of 10 000 points in four dimensions spanned by the four kinematic variables described above is used to select an optimal set of selection requirements using Monte Carlo (MC) simulation samples [13]. Since we use MC samples, this is similar to the importance-sampled grid search technique in Ref. [14]. The optimal selection for the $D^+ \to K^+\eta$ mode is found to be $\xi < 5°$, $\chi^2_{\text{iso}} > 10$, $p_\eta > 1$ GeV/c, and $p^*_{D^+} > 3$ GeV/c, and for $D^+ \to K^+\eta'$ is $\xi < 5°$, $\chi^2_{\text{iso}} > 5$, $p_{\eta'} > 1.5$ GeV/c, and $p^*_{D^+} > 3$ GeV/c. The same selection criteria are applied to the normalization modes, $D^+ \to \pi^+\eta^{(\prime)}$. Figure 2 shows the $\pi^+\eta^{(\prime)}$ and $K^+\eta^{(\prime)}$ invariant mass distributions after the final selections used for the branching fraction measurements. Possible structures, for example, from $D_s^+ \to K^+\pi^-\pi^+\pi^0$ or $D_s^+ \to K^+K^-\pi^+\pi^0$ due to particle misidentification or cross feed between η and η' are studied using MC samples; we find no indication of such background.

A fit is then performed for $D^+ \to \pi^+\eta^{(\prime)}$ candidates and the results are shown as the top two plots in Fig. 2. The signal probability density function (PDF) is modeled as the sum of a Gaussian and a bifurcated Gaussian while the combinatorial background is modeled as a linear background. The χ^2/d.o.f. of fits are 0.7 and 1.4, respectively. For fits to these DCS decays, we fix the width of the Gaussian, the two widths of the bifurcated Gaussian, and then ratio of the normalizations of the Gaussian and the bifurcated Gaussian to the values obtained from the fits to the SCS modes in order to obtain stable fits. The fixed widths are scaled according to the difference of widths observed in the signal MC samples. We examine possible systematic uncertainties due to this later. The statistical significance of the signal based on the log-likelihood ratio

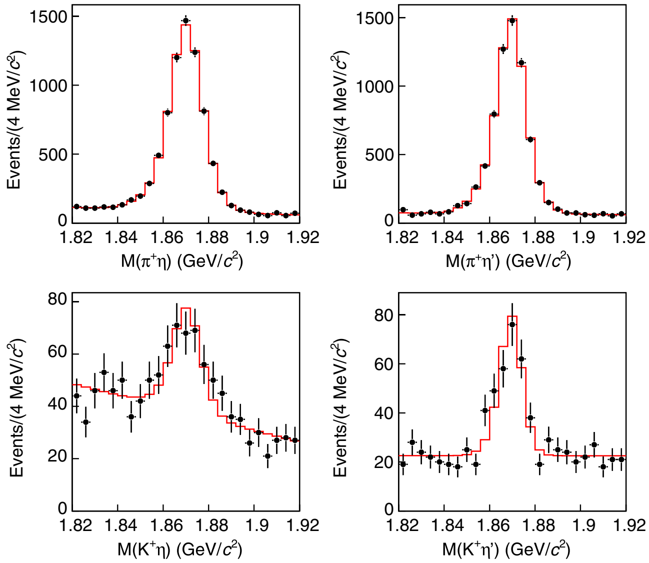

FIG. 2 (color online). The invariant mass distributions used for the branching fraction measurements. The top two plots are for the $\pi^+\eta$ (left) and $\pi^+\eta'$ (right) final states while the bottom two plots are for the $K^+\eta$ (left) and $K^+\eta'$ (right) final states. Points with error bars and histograms correspond to the data and the fit, respectively.

is 9σ and more than 10σ (σ represents 1 standard deviation from the background-only hypothesis) for $D^+ \to K^+\eta$ and $D^+ \to K^+\eta'$, respectively; the corresponding invariant mass distributions and fits are shown in the lower panel of Fig. 2. The χ^2/d.o.f. of fits to the $K^+\eta$ and $K^+\eta'$ final states are 0.8 and 0.9, respectively. In order to compute the ratio of branching fractions of DCS modes with respect to SCS modes, the signal efficiencies for the selection criteria described above are estimated with our signal MC samples. Table I lists all the information used for the branching fraction measurements.

The dominant sources of the systematic uncertainty in the branching fraction measurements are the uncertainties of the parameters that are fixed in the fits to DCS decays, and are estimated to be 3.4% (2.1%) for the $\eta(\eta')$ mode. These uncertainties are determined by refitting the data with the fit parameters varied by 1 standard deviation. Other sources include the choice of the fitting functions, estimated to be 2.7% (1.0%) for the $\eta(\eta')$ mode, and the uncertainty in the PID, estimated to be 1.1% for both modes. A summary of the systematic uncertainties for the ratio of branching fraction measurements can be found in Table II. The ratios of branching fractions are $\mathcal{B}(D^+ \to K^+\eta)/\mathcal{B}(D^+ \to \pi^+\eta) = (3.06 \pm 0.43 \pm 0.14)\%$ and $\mathcal{B}(D^+ \to K^+\eta')/\mathcal{B}(D^+ \to \pi^+\eta') = (3.77 \pm 0.39 \pm 0.10)\%$. We use the measurements of the SCS modes from Ref. [15] to calculate the absolute branching fractions. Table III shows the comparison of our branching fractions with the best present limits from Ref. [15]. While the measured branching fraction for the $K^+\eta$ mode is in agreement with the SU(3) based expectations [1,2], the $K^+\eta'$ mode is measured to be larger, by approximately 3 standard deviations.

Using the relations in Ref. [4], which give

$$|T|^2 = 3|\mathcal{A}(K^+\eta)|^2$$

$$|A|^2 = \frac{1}{2}[|\mathcal{A}(K^+\pi^0)|^2 + |\mathcal{A}(K^+\eta')|^2] - |\mathcal{A}(K^+\eta)|^2$$

$$\cos\delta_{\rm TA} = \frac{1}{2|T||A|}\Big[2|\mathcal{A}(K^+\eta)|^2 + \frac{1}{2}|\mathcal{A}(K^+\eta')|^2 - \frac{3}{2}|\mathcal{A}(K^+\pi^0)|^2\Big] \quad (1)$$

where T (A) is the tree (annihilation) amplitude and $\mathcal{A}$ is the specified decay amplitude, and from the recent branching fraction measurement of $\mathcal{B}(D^+ \to K^+\pi^0) = (1.72 \pm 0.20) \times 10^{-4}$ [15], we find that the relative final-state phase difference between the tree and annihilation in D^+ decays, $\delta_{\rm TA}$, is $(72 \pm 9)^\circ$ or $(288 \pm 9)^\circ$.

For our A_{CP} measurement in the $D^+ \to \pi^+\eta^{(\prime)}$ modes, we reoptimize our selection by maximizing $\mathcal{N}_S/\sigma_S$ where σ_S is the statistical error on the signal yield $\mathcal{N}_S$ in the simulated sample. The reoptimized requirements for $D^+ \to \pi^+\eta$ decays are: $\xi < 5^\circ$, $\chi^2_{\rm iso} > 5$, $p_\eta > 1.0$ GeV/c, and $p^*_{D^+} > 2.5$ GeV/c, and for $D^+ \to \pi^+\eta'$ are: $\xi < 5^\circ$, $\chi^2_{\rm iso} > 2$, $p_{\eta'} > 1.0$ GeV/c, and $p^*_{D^+} > 2.5$ GeV/c, respectively. These requirements are slightly less stringent than the selection criteria used for the branching fraction measurements of DCS modes. This improves the statistical sensitivity on A_{CP} by around 15%.

We determine the quantities $A_{CP}^{D^+\to\pi^+\eta^{(\prime)}}$ [16] by measuring the asymmetry in signal yield

TABLE I. Yields from the data and the signal efficiencies for the branching fraction measurements. Errors are statistical only.

Mode	Yield	Signal Efficiency (%)
$D^+ \to K^+\eta$	166 ± 23	1.35 ± 0.01
$D^+ \to K^+\eta'$	180 ± 19	1.20 ± 0.01
$D^+ \to \pi^+\eta$	6476 ± 110	1.68 ± 0.02
$D^+ \to \pi^+\eta'$	6023 ± 93	1.59 ± 0.01

TABLE II. Summary of all relative systematic uncertainties for the measurements of ratios of branching fractions.

Source	$\sigma(\frac{\mathcal{B}(D^+\to K^+\eta)}{\mathcal{B}(D^+\to\pi^+\eta)})$(%)	$\sigma(\frac{\mathcal{B}(D^+\to K^+\eta')}{\mathcal{B}(D^+\to\pi^+\eta')})$(%)
PID	1.1	1.1
Signal PDF	3.4	2.1
Fit method	2.7	1.0
Total	4.5	2.6

TABLE III. Comparison of our branching fraction results to the present best upper limit (90% C.L.) from Ref. [15]. The first and second uncertainties are statistical and systematic, respectively.

Measurement	Belle	Ref. [15]
$\mathcal{B}(D^+ \to K^+ \eta)$	$(1.08 \pm 0.17 \pm 0.08) \times 10^{-4}$	$<1.3 \times 10^{-4}$
$\mathcal{B}(D^+ \to K^+ \eta')$	$(1.76 \pm 0.22 \pm 0.12) \times 10^{-4}$	$<1.9 \times 10^{-4}$

$$A_{\rm rec}^{D^+\to\pi^+\eta^{(\prime)}} \equiv \frac{N_{\rm rec}^{D^+\to\pi^+\eta^{(\prime)}} - N_{\rm rec}^{D^-\to\pi^-\eta^{(\prime)}}}{N_{\rm rec}^{D^+\to\pi^+\eta^{(\prime)}} + N_{\rm rec}^{D^-\to\pi^-\eta^{(\prime)}}} \cong A_{CP}^{D^+\to\pi^+\eta^{(\prime)}} + A_{\rm FB}^{D^+} + A_{\epsilon}^{\pi^+}, \qquad (2)$$

where $N_{\rm rec}$ is the number of reconstructed decays. Note that we neglect the terms involving the product of asymmetries and the approximation is valid for small asymmetries. The measured asymmetry in Eq. (2) includes two contributions other than A_{CP}. One is the forward-backward asymmetry ($A_{\rm FB}^{D^+}$) due to $\gamma^* - Z^0$ interference in $e^+e^- \to c\bar{c}$ and the other is the detection efficiency asymmetry between positively and negatively charged pions ($A_{\epsilon}^{\pi^+}$). To correct for the asymmetries other than A_{CP}, we use a sample of Cabibbo-favored $D_s^+ \to \phi\pi^+$ decays, in which the expected CP asymmetry from the SM is negligible. Assuming that $A_{\rm FB}$ is the same for all charmed mesons, the difference between $A_{\rm rec}^{D^+\to\pi^+\eta^{(\prime)}}$ and $A_{\rm rec}^{D_s^+\to\phi\pi^+}$ yields the CP violation asymmetry $A_{CP}^{D^+\to\pi^+\eta^{(\prime)}}$. We reconstruct ϕ mesons via the K^+K^- decay channel, requiring the K^+K^- invariant mass to be between 1.01 and 1.03 GeV/c^2. This is the same technique as the one developed in Ref. [17].

In order to obtain A_{CP}, we subtract the measured asymmetry for $D_s^+ \to \phi\pi^+$ from that for $D^+ \to \pi^+\eta^{(\prime)}$ in three-dimensional (3D) bins, where the 3D bins are the transverse momentum, $p_{T\pi}^{\rm lab}$, and the polar angle of the π^+ in the laboratory system, $\cos\theta_{\pi}^{\rm lab}$, and the charmed meson polar angle in the center-of-mass system, $\cos\theta^*_{D^+_{(s)}}$. Simultaneous fits to the $D^+_{(s)}$ and $D^-_{(s)}$ invariant mass distributions for each bin are carried out. A double Gaussian for the signal and a linear function for the background are used as PDFs for $D_s^+ \to \phi\pi^+$. The average value over all bins is found to be $A_{\rm rec}^{D_s^+\to\phi\pi^+} = (0.17 \pm 0.13)\%$. After the subtraction of $A_{\rm rec}^{D_s^+\to\phi\pi^+}$ component, weighted averages of the A_{CP} values summed over the 3D bins are $(+1.74 \pm 1.14)\%$ and $(-0.12 \pm 1.13)\%$ for $D^+ \to \pi^+\eta$ and $D^+ \to \pi^+\eta'$, respectively, where the uncertainties originate from the finite size of the $D^+ \to \pi^+\eta$ (1.13%), $D^+ \to \pi^+\eta'$ (1.12%), and $D_s^+ \to \phi\pi^+$ (0.13%) samples. The χ^2/d.o.f. values summed over the 3D bins are $28.7/11 = 2.6$ for $D^+ \to \pi^+\eta$ and $15.7/11 = 1.4$ for $D^+ \to \pi^+\eta'$.

The dominant source of systematic uncertainty in the A_{CP} measurement is the uncertainty in the $A_{\rm rec}^{D_s^+\to\phi\pi^+}$ determination, which originates from the following sources: the statistics of the $D_s^+ \to \phi\pi^+$ sample (0.13%), possible detection asymmetry of kaons from $\phi \to K^+K^-$ (0.05%) [18], and the choice of binning for the 3D map (0.12%, 0.01%), for $D^+ \to \pi^+\eta$ and $D^+ \to \pi^+\eta'$, respectively. Another source is the fitting of the invariant mass distribution (fit interval, choice of the fitting function), which contributes uncertainties of 0.05% to $A_{CP}^{D^+\to\pi^+\eta}$, and 0.07% to $A_{CP}^{D^+\to\pi^+\eta'}$. Possible systematic uncertainties due to the fixed signal PDF parameters are estimated to be 0.01% for $A_{CP}^{D^+\to\pi^+\eta}$ and 0.07% for $A_{CP}^{D^+\to\pi^+\eta'}$. By combining all sources in quadrature, we obtain $A_{CP}^{D^+\to\pi^+\eta} = (+1.74 \pm 1.13 \pm 0.19)\%$ and $A_{CP}^{D^+\to\pi^+\eta'} = (-0.12 \pm 1.12 \pm 0.17)\%$. These are the most precise measurements of $A_{CP}^{D^+\to\pi^+\eta^{(\prime)}}$ to date.

In conclusion, we report the first observation of DCS $D^+ \to K^+\eta^{(\prime)}$ decays using a 791 fb^{-1} data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The ratios of branching fractions of DCS modes with respect to the SCS modes are $\mathcal{B}(D^+ \to K^+\eta)/\mathcal{B}(D^+ \to \pi^+\eta) = (3.06 \pm 0.43 \pm 0.14)\%$ and $\mathcal{B}(D^+ \to K^+\eta')/\mathcal{B}(D^+ \to \pi^+\eta') = (3.77 \pm 0.39 \pm 0.10)\%$. Using our DCS branching fractions and that of $D^0 \to K^+\pi^0$ from Ref. [15], the first measurement of the relative phase difference between the tree and annihilation amplitudes in D^+ decays is reported with $\delta_{\rm TA} = (72 \pm 9)^\circ$ or $(288 \pm 9)^\circ$ using the technique suggested in Ref. [4]; this is important information relevant to final-state interactions. We also search for CP asymmetries in SCS modes down to the $\mathcal{O}(\%)$ level.

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