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Studies of radiative charm decays at Belle

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Summary. — We report a measurement of the branching fractions of the radiative decays $D^0 \to V\gamma$, where $V = \phi$, $\overline{K}^{*0}$ or ρ^0. This is the first observation of the decay $D^0 \to \rho^0\gamma$. We measure preliminary branching fractions $\mathcal{B}\left(D^0 \to \phi\gamma\right) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$, $\mathcal{B}\left(D^0 \to \overline{K}^{*0}\gamma\right) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$ and $\mathcal{B}\left(D^0 \to \rho^0\gamma\right) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$, where the first uncertainty is statistical and the second systematic. We also present the first measurement of CP asymmetry in these decays. The preliminary values are $\mathcal{A}_{CP}\left(D^0 \to \phi\gamma\right) = -0.094 \pm 0.066 \pm 0.001$, $\mathcal{A}_{CP}\left(D^0 \to \overline{K}^{*0}\gamma\right) = -0.003 \pm 0.020 \pm 0.000$ and $\mathcal{A}_{CP}\left(D^0 \to \rho^0\gamma\right) = 0.056 \pm 0.151 \pm 0.006$. We also present the results of the search for the rare charm decay $D^0 \to \gamma\gamma$, resulting in an upper limit on the branching fraction $\mathcal{B}r(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ at 90% confidence level, the most restrictive limit to date.

1. – Introduction

The radiative decays $D^0 \to V\gamma$, where V is a vector meson, could be sensitive to New Physics (NP) via CP asymmetry. Theoretical studies [1,2] predict that in Standard Model (SM) extensions with chromomagnetic dipole operators, $\mathcal{A}_{CP}$ can rise to several percent for $V = \phi, \rho^0$, compared to the $\mathcal{O}(10^{-3})$ SM expectation.

The current world average values of the branching fractions are $(2.70 \pm 0.35) \times 10^{-5}$ (ϕ mode) and $(32.7 \pm 3.4) \times 10^{-5}$ ($\overline{K}^{*0}$mode) [3-5]. For the ρ^0 mode, the upper limit is $\mathcal{B}\left(D^0 \to \rho^0\gamma\right) < 24 \times 10^{-5}$ (90% C.L.) [3, 6]. No study of CP violation in decays $D^0 \to V\gamma$ has been conducted to date.

We present here a measurement of the branching fractions and CP asymmetries in decays $D^0 \to V\gamma$, where $V \in \{\phi,\ \overline{K}^{*0},\ \rho^0\}$. This is the first observation and branching fraction measurement of the decay $D^0 \to \rho^0\gamma$. The analysis is based on 943 fb^{-1} of data collected by the Belle detector, operating at the asymmetric KEKB e^+e^- collider [7].

We also present a search for the rare charm decay $D^0 \to \gamma\gamma$ [8], conducted on 832 fb^{-1} of Belle data. This decay represents a good probe for NP, as the SM prediction for the branching fraction, which is of the order of $\mathcal{O}(10^{-8})$, can be enhanced by several

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orders of magnitude by NP contributions. The Minimal Supersymmetric Standard Model suggests that the exchange of gluinos can enhance the $D^0 \to \gamma\gamma$ branching ratio up to 6×10^{-6} [9,10].

The decay $D^0 \to \gamma\gamma$ has not been observed yet. The best upper limit, set by previous experiments, is from the measurement conducted by the *BABAR* experiment, yielding a branching fraction of $\mathcal{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ (90% C.L.) [11].

2. – Analysis $D^0 \to V\gamma$

The D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi^+$ in order to provide a tag on the D^0 flavor and to suppress combinatorial background. The signal decays are reconstructed in the following decays of the vector mesons: $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$ and $\rho^0 \to \pi^+\pi^-$.

The dominant background arises from decays comprising a π^0 instead of a photon, with the π^0 subsequently decaying into a pair of photons and one photon being missed in the reconstruction. To suppress such events, a dedicated π^0 veto is developed, comprising a neural network variable obtained from two mass veto variables. The signal photon is paired once with each other photon in the event with an energy above 30 MeV, and once with each photon with an energy above 75 MeV. The pair in each set whose diphoton mass lies closest to $m(\pi^0)$ is fed to the neural network. The final criterion on the veto variable rejects about 60% of background while losing about 15% of signal.

Both the branching fraction and $\mathcal{A}_{CP}$ are obtained via normalization to other decay channels. Such an approach enables the cancellation of several sources of systematic uncertainties. The signal branching fraction $\mathcal{B}_{\rm sig}$ is given by

$$\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm norm} \times \frac{N_{\rm sig}}{N_{\rm norm}} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}, \tag{1}$$

where N is the extracted yield, ε the reconstruction efficiency and $\mathcal{B}$ the branching fraction for signal and normalization modes, respectively. For $\mathcal{B}_{\rm norm}$ the world-average value [3] is used. The extracted raw asymmetry

$$A_{\rm raw} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} \tag{2}$$

relates to the physical CP asymmetry $\mathcal{A}_{CP}$ as $A_{\rm raw} = \mathcal{A}_{CP} + A_{\rm FB} + A_{\varepsilon}^{\pm}$. Here, $A_{\rm FB}$ is the forward-backward production asymmetry [3], and $A_{\varepsilon}^{\pm}$ is the asymmetry due to different reconstruction efficiencies for positively and negatively charged particles. Both can be eliminated through a relative measurement of $\mathcal{A}_{CP}$, if the charged final-state particles are identical. The chosen normalization modes are thus $D^0 \to K^+K^-$ (ϕ mode) $D^0 \to K^-\pi^+$ ($\overline{K}^{*0}$ mode) and $D^0 \to \pi^+\pi^-$ (ρ^0 mode). The CP asymmetry of the signal modes is obtained as $\mathcal{A}_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + \mathcal{A}_{CP}^{\rm norm}$, where $\mathcal{A}_{CP}^{\rm norm}$ is the nominal value of CP asymmetry of the normalization modes [3].

2·1. *Signal extraction.* – To extract the signal yield and CP asymmetry, a simultaneous two-dimensional unbinned extended maximum likelihood fit of D^0 and $\overline{D}^0$ samples is performed. The fit variables are the invariant mass of the reconstructed D^0 meson and the cosine of the helicity angle θ_H, defined as the angle between the D^0 and the

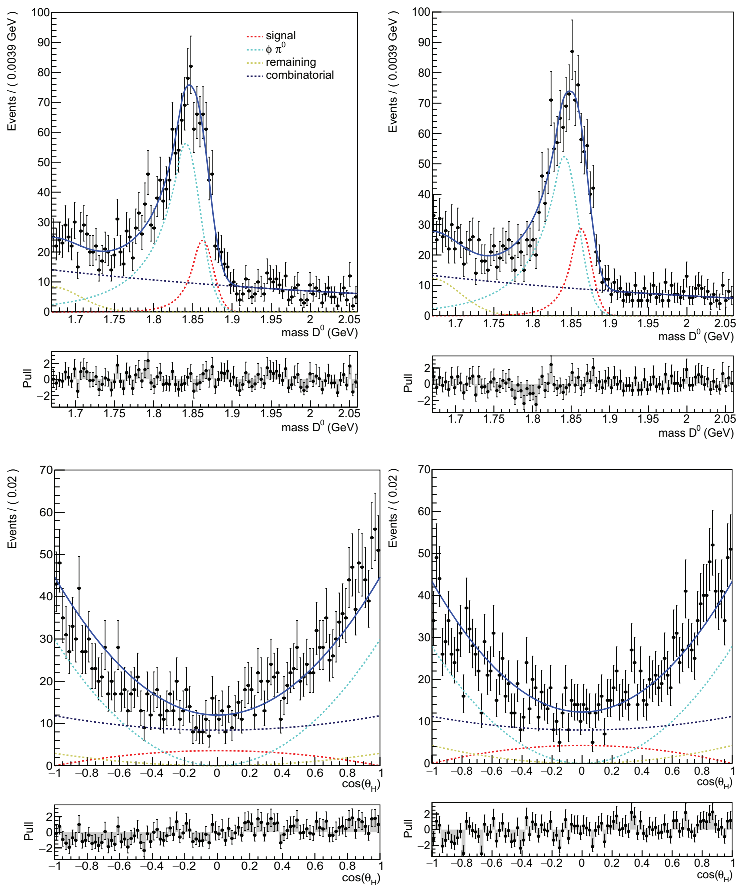


Fig. 1. – The $M(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the ϕ mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.

positively or negatively charged hadron in the rest frame of the V meson. The final full-reconstruction efficiencies are 9.7% (ϕ mode), 7.8% ($\overline{K}^{*0}$ mode) and 6.8% (ρ^0 mode).

The fit results are shown in figs. 1, 2 and 3 for the ϕ, $\overline{K}^{*0}$ and ρ^0 modes, respectively. The signal component is denoted with the dashed red line. The extracted signal yields are 524 ± 35 (ϕ mode), 9104 ± 396 ($\overline{K}^{*0}$ mode) and 500 ± 85 (ρ^0 mode). The extracted raw asymmetries are -0.091 ± 0.066 (ϕ mode), -0.002 ± 0.020 ($\overline{K}^{*0}$ mode) and 0.064 ± 0.151 (ρ^0 mode). Here, the uncertainties are statistical only.

Figure 4 shows the signal enhanced plots for all three signal modes, plotting $M(D^0)$ in a reduced range of $\cos\theta_H$.

2˙2. *Analysis of normalisation modes.* – The analysis of the normalization modes is based on the previous analysis of the same modes by Belle [12]. The signal yield is extracted via background subtraction in a signal window (SW) of $M(D^0)$, with the background being estimated from a symmetrical upper and lower sideband (USB and LSB). Based on MC, the fraction of background events in the signal window compared to all events in sidebands $f = \frac{(N_{\mathrm{SW}}^{\mathrm{bkg}})_{MC}}{(N_{\mathrm{LSB}}+N_{\mathrm{USB}})_{MC}}$ is calculated and then used to calculate the

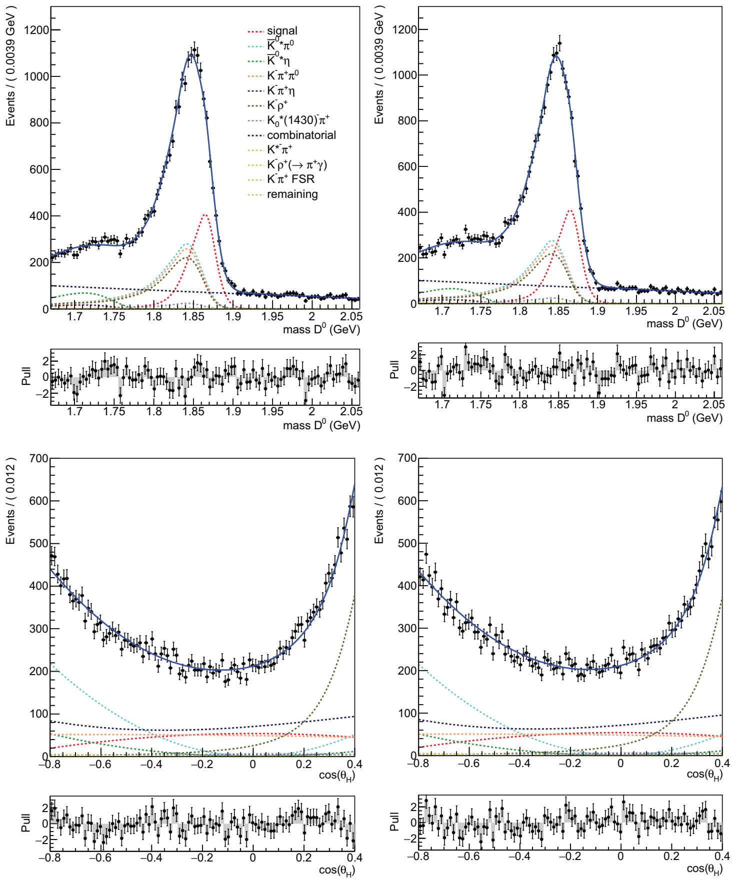


Fig. 2. – The $M(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the $\overline{K}^{*0}$ mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.

number of background events in data in the signal window $(N_{\mathrm{SW}}^{\mathrm{bkg}})_{\mathrm{DATA}} = f \times (N_{\mathrm{LSB}} + N_{\mathrm{USB}})_{\mathrm{DATA}}$.

The efficiencies are 22.7% for K^+K^-, 27.0% for $K^-\pi^+$ and 21.4% for $\pi^+\pi^-$. We extract a signal yield of 362 274 events for K^+K^-, 4.02×10^6 events for $K^-\pi^+$ and 127 683 events for $\pi^+\pi^-$. The extracted raw asymmetries are $(2.2 \pm 1.7) \times 10^{-3}$ (K^+K^-), $(1.3 \pm 0.5) \times 10^{-3}$ $(K^-\pi^+)$ and $(8.1 \pm 3.0) \times 10^{-3}$ $(\pi^+\pi^-)$.

2˙3. *Systematic uncertainties*. – All systematic uncertainties are summarized in table I. The systematic uncertainties from reconstruction efficiencies that do not cancel between the signal and normalisation modes are the photon reconstruction efficiency, and uncertainties from the selection critera imposed on the total energy released in the decay (q), the π^0 veto and the variable E_9/E_{25}, which is the ratio of the energy deposited in a 3×3 array of ECL crystals *vs.* the energy deposited in the enclosing 5×5 array. Additionally, systematics arise from signal parametrisation, background parametrisation, and signal extraction method in the normalisation modes.

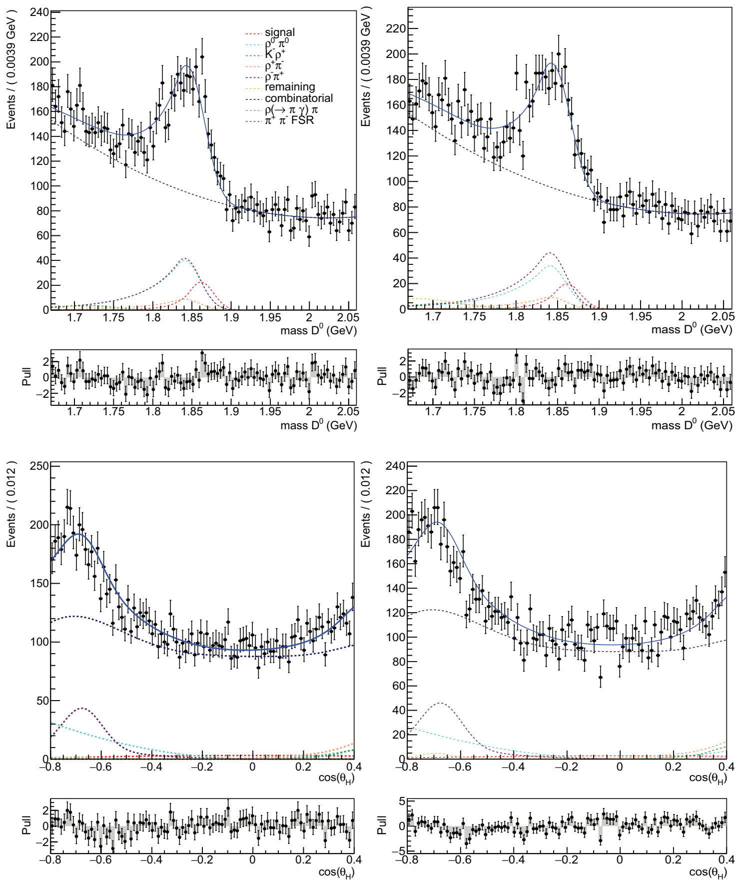
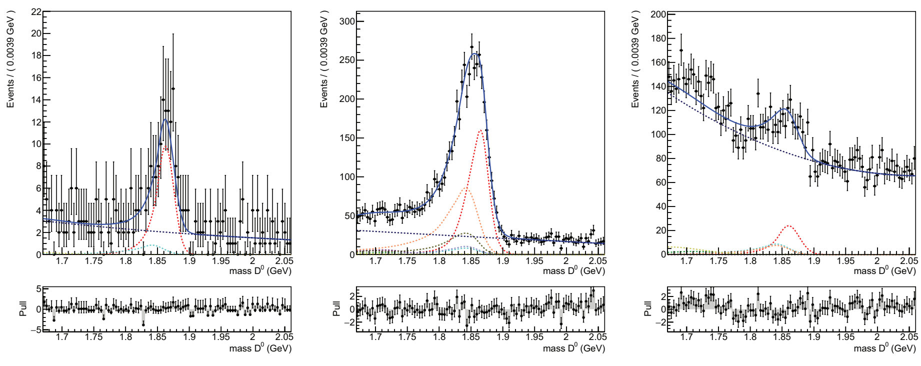


Fig. 3. – The $M(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the ρ^0 mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.



(a) ϕ mode (b) $\overline{K}^{*0}$ mode (c) ρ^0 mode

Fig. 4. – Signal enhanced plots of $M(D^0)$ in a reduced $\cos(\theta_H)$ window for all three signal modes.

Table I. – *Systematic uncertainties for the analysis $D^0 \to V\gamma$.*

	ϕ mode		$\overline{K}^{*0}$ mode		ρ^0 mode	
	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]	$\mathcal{B}$ [%]	$\mathcal{A}_{CP}$ [$\times 10^{-3}$]
γ rec. eff.	2	–	2	–	2	–
q	1.16	–	1.16	–	1.16	–
π^0 veto	0.5	–	0.5	–	0.5	–
$\frac{E_9}{E_{25}}$	0.96	–	0.96	–	0.96	–
signal parametrisation	1.39	0.32	–	–	2.33	4.29
background parametrisation	0.95	0.30	2.81	0.41	3.00	3.78
norm. modes systematics	0.05	0.46	0.00	0.01	0.14	0.54
total	3.06	0.64	3.8	0.41	4.58	5.74

2.4. *Results*. – The preliminary branching fractions are

$$\mathcal{B}\left(D^0 \to \phi\gamma\right) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5},$$
$$\mathcal{B}\left(D^0 \to \overline{K}^{*0}\gamma\right) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4},$$
$$\mathcal{B}\left(D^0 \to \rho^0\gamma\right) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5},$$

where the first uncertainty is statistical and the second systematic. The result of the ϕ mode is improved compared to the previous Belle result and is consistent with the world average value [3]. Our branching fraction of the $\overline{K}^{*0}$ mode is $3.3\,\sigma$ away from the result of the BABAR analysis. For the ρ^0 mode, this analysis reports the first observation of the decay. The significance of the observation is greater than $5\,\sigma$, including systematic uncertainties.

We also report the first-ever measurement of $\mathcal{A}_{CP}$ in the decays $D^0 \to V\gamma$. The preliminary values are

$$\mathcal{A}_{CP}\left(D^0 \to \phi\gamma\right) = -(0.094 \pm 0.066 \pm 0.001),$$
$$\mathcal{A}_{CP}\left(D^0 \to \overline{K}^{*0}\gamma\right) = -(0.003 \pm 0.020 \pm 0.000),$$
$$\mathcal{A}_{CP}\left(D^0 \to \rho^0\gamma\right) = +(0.056 \pm 0.151 \pm 0.006).$$

We report no observation of CP asymmetry in any of the $D^0 \to V\gamma$ decay modes.

3. – Analysis $D^0 \to \gamma\gamma$

The D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi^+$ in order to suppress combinatorial background. Another prominent source of background are

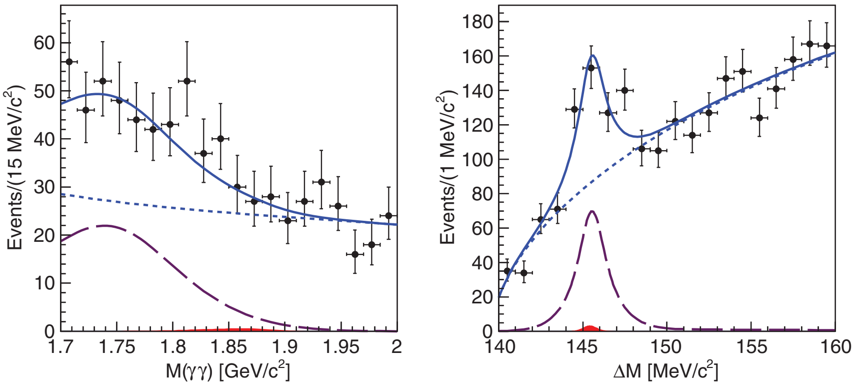


Fig. 5. – 2-dimensional fit in $M(D^0)$ (left) and ΔM (right). Blue (purple) dashed line denotes the combinatorial (peaking) background, while the red histogram shows the signal component.

physical decays with a π^0 and/or η meson decaying to a pair of photons: $D^0 \to \pi^0\pi^0$, $D^0 \to \eta\pi^0, D^0 \to \eta\eta, D^0 \to K^0_S(\to \pi^0\pi^0)\pi^0$, $D^0 \to K^0_L\pi^0$. These background types are suppressed with a dedicated $\pi^0(\eta)$ veto and suppression of merged ECL clusters with a constraint imposed on the variable E_9/E_{25}.

The branching fraction is calculated through normalisation to the decay $D^0 \to K^0_S\pi^0$.

3˙1. *Signal extraction.* – Signal is extracted through a 2-dimensional unbinned extended maximum likelihood fit in $M(D^0)$ and the mass difference between the $D^0$and D^{*+}, $\Delta M = M(D^{*+}) - M(D^0)$. The efficiency is 7.3%. We extract a signal yield of 4 ± 15 events. The fit results are shown in fig. 5.

The same fit is used for the normalisation channel. The efficiency is 7.2%. We extract a yield of 343050 ± 673 events.

3˙2. *Systematic uncertainties.* – The systematic uncertainties are summarised in table II.

3˙3. *Calculation of upper limit.* – In the absence of signal, a frequentist method is used to estimate the upper limit on the branching fraction at a 90% confidence level.

Table II. – *Systematic uncertainties for the analysis $D^0 \to \gamma\gamma$.*

cut variation	$\pm 6.8\%$
signal PDF shape	$^{+4.0}_{-2.4}$ events
γ rec. eff.	$\pm 4.4\%$
K^0_S reconstruction	$\pm 0.7\%$
π^0 identification	$\pm 4.0\%$
$\mathcal{B}r(D^0 \to K^0_S\pi^0)$	$\pm 3.3\%$

The systematic uncertainties are included in the calculation. The final result is

$$\mathcal{B}r(D^0 \to \gamma\gamma) < 8.4 \times 10^{-7} \tag{3}$$

at 90% C.L [8]. This result represents by far the most stringent upper limit to date.

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