

# Recent results on the charmed hadron systems at Belle

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CP violation and mixing in the charm meson system are expected to be very small in the standard model (SM), hence it can be a good probe to search for new physics beyond the SM. The Belle experiment, with high statistics  $e^+e^-$  collision data taken at the KEKB energy-asymmetric collider using the Belle detector, is a very good place to study charmed hadron systems. In this presentation we report recent results from Belle on CP violation and mixing in the neutral D meson system. We also present recent results from Belle in the charmed baryon spectroscopy, including new measurements of mass, width, and absolute branching fractions of various charmed baryons.

The Belle experiment is excellent place to study charmed hadron systems since it has large relative cross-section for charmed hadron production and clean event environment combined with high luminosity. In this proceeding, we report recent results from Belle on CP violation and mixing in the neutral D meson system. We also present result from Belle in the charmed baryon spectroscopy.

## 1 Neutral D meson system

The mixing rate and the size of CP violation (CPV) in charm sector is expected to be very small in standard model (SM) [1, 2]. Thus, the measurement of  $D^0 - \bar{D}^0$  mixing and CPV could provide probe to search for beyond SM [3, 4].  $D^0 - \bar{D}^0$  mixing occurs because the mass eigenstate ( $|D_{H,L}\rangle$ ) is different from flavor eigenstate ( $|D^0\rangle, |\bar{D}^0\rangle$ ). The mass eigenstate can be represented by flavor eigenstate, namely  $|D_{H,L}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ . The phenomenology of meson mixing is described by two parameters,  $x = \Delta M/\Gamma$  and  $y = \Delta\Gamma/2\Gamma$ , where  $\Delta M$  and  $\Delta\Gamma$  are mass and width difference between two mass eigenstates,  $\Gamma$  is average decay width of mass eigenstates. The direct CPV can be measured by decay rate comparison between particle and anti-particle system. The indirect CPV parameters are  $|q/p|$  and  $\arg(q/p)$ , the former is CPV in mixing and the latter is CPV in interference of decay with and without mixing.

### 1.1 Mixing in $D^0 \rightarrow K^+\pi^-$ decay [5]

The mixing parameters of the  $K^0$ ,  $B^0$  and  $B_s^0$  mesons are well established [6]. Recently the  $D^0$  mixing has been observed in hadron collider experiment [7, 8]. ; This is first observation of  $D^0 - \bar{D}^0$  mixing from  $e^+e^-$  collider by measuring time dependent ratio of the  $D^0 \rightarrow K^+\pi^-$  and  $D^0 \rightarrow K^-\pi^+$  decay. We named the  $D^0 \rightarrow K^+\pi^-$  decay as wrong sign (WS) decay

and  $D^0 \rightarrow K^- \pi^+$  decay as right sign (RS) decay. The RS decay amplitude is sum of the amplitude from Cabibbo-favored (CF) decay  $D^0 \rightarrow K^- \pi^+$  and  $D^0 - \bar{D}^0$  mixing followed by the doubly Cabibbo-suppressed (DCS) decay  $\bar{D}^0 \rightarrow K^- \pi^+$ , where the later is much smaller than former one so it is neglected. The WS decay amplitude is sum of two comparable amplitudes from DCS decay  $D^0 \rightarrow K^+ \pi^-$  and  $D^0 - \bar{D}^0$  mixing followed by the CF decay  $\bar{D}^0 \rightarrow K^+ \pi^-$ . Then time-dependent WS to RS decay rates are  $\Gamma_{RS}(\tilde{t}/\tau) \approx |A_{CF}|^2 e^{-\tilde{t}/\tau}$  and  $\Gamma_{WS}(\tilde{t}/\tau) \approx |A_{CF}|^2 e^{-\tilde{t}/\tau} (R_D + \sqrt{R_D} y' \frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4} (\frac{\tilde{t}}{\tau})^2)$ , respectively, the  $\tilde{t}$  proper true decay time,  $\tau$  is  $D^0$  lifetime,  $|A_{CF}|$  is the CF decay amplitude,  $R_D$  is the ratio of DCS to CF decay rates,  $x' = x \cos \delta + y \sin \delta$  and  $y' = y \cos \delta - x \sin \delta$  where  $\delta$  is the strong phase difference between the DCS and CF decay. The time resolution in B factory is comparable with  $D^0$  decay time, so we extract the time resolution function  $R(t/\tau - \tilde{t}/\tau)$  from  $D^0$  mean decay time. Then the WS, RS decay rate ratio becomes  $\mathbf{R}(t/\tau) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS} R(t/\tau - \tilde{t}/\tau) d(\tilde{t}/\tau)}{\int_{-\infty}^{+\infty} \Gamma_{RS} R(t/\tau - \tilde{t}/\tau) d(\tilde{t}/\tau)}$ .

The  $\chi^2/ndf$  for mixing hypothesis is 4.2/7 and no mixing hypothesis is 33.5/9, the mixing hypothesis excludes non-mixing hypothesis with  $5.1\sigma$ .

## 1.2 Mixing and indirect CPV in $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decay [9]

So far there is no evidence of indirect CP violation in D meson system. Experimental estimation of indirect CP violation is  $1 - |q/p| = 0.12 \pm 0.17$  [6]. This study is search for indirect CP violation using  $D^0 \rightarrow K_s^0 \pi^+ \pi^-$  decay channel. The analysis is done with three dimensional decay amplitude analysis, two is dalitz plot variable  $m(K_s^0 \pi^+)$  and  $m(K_s^0 \pi^-)$ , and the rest one is time. As a result, the indirect parameter is  $|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$  and  $\arg(q/p)^\circ = -6 \pm 11 \pm 3^{+3}_{-4}$ . It shows no evidence of indirect CP violation.

## 1.3 CPV in $D^0 \rightarrow \pi^0 \pi^0$ decay [10]

CP violation in charm decay is very small to observe so experimental observation could indicate new physics. So far only existing CP violation study of  $D^0 \rightarrow \pi^0 \pi^0$  decay is from CLEO [11], the direct CP asymmetry  $\Delta A_{CP}$  is  $(0.1 \pm 4.8)\%$ . In this study, direct CPV is estimated using  $D^0 \rightarrow \pi^0 \pi^0$  decay. The asymmetry is  $A_{rec} = \frac{N_{rec}^{D^{*+} \rightarrow D^0 \pi_x^+} - N_{rec}^{D^{*-} \rightarrow D^0 \pi_x^+}}{N_{rec}^{D^{*+} \rightarrow D^0 \pi_x^+} + N_{rec}^{D^{*-} \rightarrow D^0 \pi_x^+}} \approx A_{CP} + A_{FB}(\cos \theta^*)$ . The  $A_{CP}$  can be extracted removing  $A_{FB}$  using asymmetry on the  $\cos \theta^*$  where  $\theta^*$  is polar angle of  $D^*$ . Using decay channel  $D^0 \rightarrow \pi^0 \pi^0$ , the measured asymmetry is  $A_{CP}(D^0 \rightarrow \pi^0 \pi^0) = (-0.03 \pm 0.64(stat) \pm 0.10(sys))\%$  which is consistent with no CP violation.

# 2 New measurement of charmed baryon

## 2.1 Branching fraction of $\Lambda_c^+ \rightarrow p K^- \pi^+$ decay [12]

A number of charmed baryons decay into  $\Lambda_c^+$ . And  $\Lambda_c^+ \rightarrow p K^- \pi^+$  is the reference mode for the measurement of branching fractions of the  $\Lambda_c^+$  baryon, so it's important to measure the absolute branching fraction. The Particle Data Group combines several measurements from the ARGUS and CLEO Collaborations to determine  $\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+) = (5.0 \pm 1.3)\%$  [13, 14]. The dominant contribution to the uncertainty is from the model dependence of branching fraction extraction [15]. In the proceeding, we present the first model-independent absolute branching fraction measurement of the  $\Lambda_c^+ \rightarrow p K^- \pi^+$  decay.

The absolute branching fraction is given by  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = \frac{N(\Lambda_c^+ \rightarrow pK^-\pi^+)}{N_{inc}^{\Lambda_c^+} f_{bias} \varepsilon(\Lambda_c^+ \rightarrow pK^-\pi^+)}$ ,

where  $N_{inc}^{\Lambda_c^+}$  is the number of inclusively reconstructed  $\Lambda_c^+$ ,  $N(\Lambda_c^+ \rightarrow pK^-\pi^+)$  is the number of reconstructed  $\Lambda_c^+ \rightarrow pK^-\pi^+$  within inclusive  $\Lambda_c^+$  sample,  $\varepsilon(\Lambda_c^+ \rightarrow pK^-\pi^+)$  is reconstruction efficiency of  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay within inclusive  $\Lambda_c^+$  sample,  $f_{bias}$  is the factor that takes into account potential dependance of the inclusive  $\Lambda_c^+$  reconstruction efficiency on the  $\Lambda_c^+$  decay mode.

To get the inclusive  $\Lambda_c^+$  baryons, we used missing mass method for  $e^+e^- \rightarrow c\bar{c} \rightarrow D^{(*)-} \bar{p}\pi^+\Lambda_c^+$  decay. Then we search the decay product of  $\Lambda_c^+ \rightarrow pK^-\pi^+$  decay in the sample of inclusive  $\Lambda_c^+$  baryon. The efficiency of  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $f_{bias}$  are determined by MC simulation. The MC simulation shows that  $\Lambda_c^+$  inclusive reconstruction efficiency weakly depends on the  $\Lambda_c^+$  decay mode, therefore we need correction for true inclusive  $\Lambda_c^+$  sample. The factor  $f_{bias} = \varepsilon_{\Lambda_c^+ \rightarrow pK^-\pi^+}^{inc} / \bar{\varepsilon}_{\Lambda_c^+}^{inc}$  is necessary for this correction.

As a result, the branching fraction is  $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (6.84 \pm 0.24(stat) \pm_{-0.27}^{+0.21}(sys))\%$ , that is constant with previous result and this result improves the previous measurement by factor 5.

## 2.2 Measurement of mass and width of the $\Sigma_c(2455)^{0/++}$ and $\Sigma_c(2520)^{0/++}$ baryons [16]

The properties of the  $\Sigma_c^{0/++}$  baryons have been measured many experiments, but uncertainty remains large [15]. For example, decay width of the  $\Sigma_c^{0/++}$  is 10% of its central value, and the mass splitting  $m(\Sigma_c(2455)^{++}) - m(\Sigma_c(2455)^0)$  is about 40%. Because of mass hierarchy between u and d quarks, mass of  $\Sigma_c^0(udc)$  should be heavier than  $\Sigma_c^{++}(uuc)$ . However the experimental results shows opposite mass hierarchy with large error [17]. In this situation, precise mass and width measurement is necessary.

The  $\Sigma_c^{0/++}$  baryons are reconstructed via  $\Sigma_c^{0/++} \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi_s^-/+$  decay channel, where  $\pi_s$  is low momentum pion. The feed down from  $\Lambda_c(2595, 2620)^+$  is removed with mass cut on  $m(\Lambda_c^+\pi^+\pi^-)$ ,

The fitting functions for signal is Breit-Wigner function convolved with detector resolution function. The random background function is threshold function. There is feed down around  $\Delta M = 185 \text{ MeV}/c^2$ , we confirmed that the origin of the peak is from  $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ . This peak is described by Gaussian function. The  $\chi^2/ndf$  for fit result is 350/347 for zero charge, 343/350 for double charge. The mass and width from fitting result is on table 1. This result shows better uncertainty than previous result.

	$\Delta M_0(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$M_0(\text{MeV}/c^2)$
$\Sigma_c(2455)^0$	$167.29 \pm 0.01 \pm 0.02$	$1.76 \pm 0.04_{-0.21}^{+0.09}$	$2453.75 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2455)^{++}$	$167.51 \pm 0.01 \pm 0.02$	$1.84 \pm 0.04_{-0.20}^{+0.07}$	$2453.97 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2520)^0$	$231.98 \pm 0.11 \pm 0.04$	$15.41 \pm 0.41_{-0.32}^{+0.20}$	$2518.44 \pm 0.11 \pm 0.04 \pm 0.14$
$\Sigma_c(2520)^{++}$	$231.99 \pm 0.10 \pm 0.02$	$14.77 \pm 0.25_{-0.30}^{+0.18}$	$2518.45 \pm 0.10 \pm 0.02 \pm 0.14$

Table 1: The measurement of mass and width of the  $\Sigma_c(2455)^{0/++}$  and  $\Sigma_c(2520)^{0/++}$ . The first error is statistical error and second error is systematical error. The third error on  $M_0$  is from mass error of  $\Lambda_c^+$

### 2.3 Search for doubly charmed baryon and charmed strange baryon at Belle [18]

In recent years, there has been significant progress in charmed baryon spectroscopy. So far, there are no experimentally established doubly charmed baryon. The SELEX collaboration reported evidence of  $\Xi_{cc}^+$  in the  $\Lambda_c^+ K^- \pi^+$  and  $p D^+ K^-$  final state [19]. However, the result is not supported by FOCUS, BABAR, Belle nor LHCb. In this study, we improve the search using more data and more channels.

The first decay channel is  $\Xi_{cc}^{+(+) } \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+)$  and  $\Lambda_c^+ \rightarrow p K^- \pi^+$ . We searched the mass region of  $3.2 \sim 4.0 \text{ GeV}/c^2$ , no significance signal is seen in the data. The local significance is lower than  $3\sigma$ . The upper limit of production cross section and Branching fraction with 95% C.L. is around  $10 \text{ fb}^{-1}$ .

The second decay channel is  $\Xi_{cc}^{+(+) } \rightarrow \Xi_x^0 \pi^+ (\pi^+)$  and  $\Xi_c^0 \rightarrow \Xi^0 \pi^-, \Lambda K^- \pi^+, p K^- K^- \pi^+$ . We searched same mass range with first decay channel, still there is no significant signal over mass range. The highest signal is around  $3.553 \text{ GeV}/c^2$ , but it is not significant with look elsewhere effect.

And we also searched the strange charmed baryon  $\Xi_c^+(3055)$  and  $\Xi_c^+(3123)$ , using the decay channel  $\Xi_c^+(3055, 3123) \rightarrow \Lambda_c^+ K^- \pi^-$  over the mass range  $2.9 \sim 3.2 \text{ GeV}/c^2$ . We observed the significant signal of  $\Xi_c^+(3055)$  with  $6.8\sigma$ , while no peak of  $\Xi_c^+(3123)$ . The upper limit of  $\Xi_c^+(3123)$  cross section and branching ratio is  $1.6 \pm 0.6 \pm 0.2 \text{ fb}^{-1}$ .

In summary, searching  $\Xi_{cc}^{+(+) }$  using more data and more decay channels doesn't show the signal over the mass range of  $3.2 \sim 4.0 \text{ GeV}/c^2$ . For the strange charmed baryon search, we observed  $\Xi_c^+(3055)$  with  $6.8\sigma$ , but couldn't see the peak of  $\Xi_c^+(3123)$ .

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