Experimental Constraints on the Spin and Parity of the $\Lambda_c(2880)^+$

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We report the results of several studies of the $\Lambda_c^+$ decay into $\pi^+\pi^-X$ final state in continuum $e^+e^-$ annihilation data collected by the Belle detector. An analysis of angular distributions in $\Lambda_c(2880)^+\rightarrow\Sigma_c(2455)^{0++,\pi^+\pi^-}$ decays strongly favors a $\Lambda_c(2880)^+\rightarrow\Sigma_c(2455)^{0++,\pi^+\pi^-}$ decay and measure the ratio of $\Lambda_c(2880)^+$ partial widths $\Gamma(\Sigma_c(2520)^+)\rightarrow\Sigma_c(2455)^{0++,\pi^+\pi^-}$ decay and measure $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters. These studies are based on a 553 fb$^{-1}$ data sample collected at or near the $\Upsilon(4S)$ resonance, at the KEKB collider.

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2450 MeV/c^2 < M < 2458 MeV/c^2. Whereas 35% of signal events pass this cut, only 12% of background events do so. From MC simulation we find that the mass resolution for the \( \Lambda_c(2880)^+ \to \Sigma_c(2455)^0 \pi^+ \pi^- \) decays depends strongly on the decay angle \( \theta \), defined as the angle between the pion momentum in the \( \Lambda_c(2880)^+ \) rest frame and the boost direction of the \( \Lambda_c(2880)^+ \). To assure good resolution for the \( \Lambda_c(2880)^+ \) mass and width measurement we require \( \cos \theta > 0 \). This requirement also helps to suppress combinatorial background. The resulting \( M(\Lambda_c^+ \pi^+ \pi^-) \) distribution is shown in Fig. [1] One can see clear peaks in the \( \Lambda_c(2765)^+ \) and \( \Lambda_c(2880)^+ \). A peak in the region \( M = 2940 \) MeV/c^2 is associated with the \( \Lambda_c(2940)^+ \) baryon recently observed in the \( D^0 \pi \) final state by BaBar [10]. Scattered \( \Sigma_c(2455) \) sidebands, which are also shown in Fig. [1] are featureless in the region of the \( \Lambda_c(2940)^+ \). The \( \Sigma_c(2455) \) sidebands are defined as \( 2438 \) MeV/c^2 < \( M(\Lambda_c^+ \pi^-) < 2464 \) MeV/c^2 and \( 2462 \) MeV/c^2 < \( M(\Lambda_c^+ \pi^-) < 2490 \) MeV/c^2.

We perform a binned likelihood fit to the \( \Lambda_c^+ \pi^+ \pi^- \) mass spectrum of Fig. [1] to extract the parameters and yields of the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \). The fitting function is a sum of three components: \( \Lambda_c(2880)^+ \) signal, \( \Lambda_c(2940)^+ \) signal and combinatorial background functions. As shown below, the favored spin-parity assignment for the \( \Lambda_c(2880)^+ \) is \( \frac{5}{2}^+ \), therefore the \( \Lambda_c(2880)^+ \) signal is parameterized by an F-wave Breit-Wigner function convolved with the detector resolution function, determined from MC (\( \sigma = 2.2 \) MeV/c^2). The \( \Lambda_c(2940)^+ \) signal is an S-wave Breit-Wigner function convolved with the detector resolution function (\( \sigma = 2.4 \) MeV/c^2). The background is parameterized by a third-order polynomial. The fit is shown in Fig. [1] and the results are summarized in Table [1]. The signal yield is defined as the integral of the Breit-Wigner function over a \( \pm 2.5 \Gamma \) interval.

The normalized \( \chi^2 \) of the fit is \( \chi^2/d.o.f. = 132.2/134 \). If the \( \Lambda_c(2940)^+ \) signal is removed from the fit, the double log likelihood changes by 59.8, which corresponds for 3 degrees of freedom to a signal significance of 7.2 standard deviations.

To estimate the systematic uncertainty on the results of the fit we vary the background parameterization, using a fourth-order polynomial and the inverse of a third-order polynomial. We include the \( \Lambda_c(2765)^+ \) signal region into the fit interval, parameterizing the \( \Lambda_c(2765)^+ \) signal by an S-wave Breit-Wigner function. The \( \Lambda_c(2765)^+ \) mass and width determined from the fit are \( M = (2761 \pm 1) \) MeV/c^2 and \( \Gamma = (73 \pm 5) \) MeV. We vary the selection requirements; we take into account the uncertainty in the \( \Lambda_c^+ \) mass of \( \pm 0.14 \) MeV/c^2 [14], the mass scale uncertainty of \( \pm 0.21 \) MeV/c^2 [15] and the uncertainty in the detector resolution of \( \pm 10\% \) as estimated by comparison of the inclusive \( \Lambda_c^+ \to pK^- \pi^- \) signal in data and MC. In the region between the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) signals the fit is systematically below the data points, which might be due to a presence of an additional resonance or due to interference. We take into account these possibilities as a systematic uncertainty. In each case we consider the largest positive and negative variation in the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) parameters to be the systematic uncertainty from this source; each term is then added in quadrature to give the total systematic uncertainty, quoted in Table [1]. The main sources of the systematic uncertainty are a possible contribution of the \( \Lambda_c(2765)^+ \) tail into the fit region (the shape of the tail is not well constrained) and the excess of events between the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) signals. None of the variations in the analysis alters the \( \Lambda_c(2940)^+ \) signal significance to less than 6.2 standard deviations.

For further analysis, we remove the \( \cos \theta > 0 \) requirement. To study the resonant structure of the \( \Lambda_c(2880)^+ \to \Lambda_c^+ \pi^+ \pi^- \) decays we fit the \( \Lambda_c^+ \pi^+ \pi^- \) mass spectrum in \( M(\Lambda_c^+ \pi^+ \pi^-) \) bins. By isospin symmetry, we expect equally many decays to proceed via a doubly charged \( \Sigma_c(2455) \) (\( \Sigma_c(2520) \)) as via a neutral one. Since the corresponding doubly charged and neutral channels are kinematically separated in phase space, we combine the \( M(\Lambda_c^+ \pi^+ \pi^-) \) distributions for \( M(\Lambda_c^+ \pi^-) \) and \( M(\Lambda_c^+ \pi^-) \) bins. To fit the \( \Lambda_c^+ \pi^+ \pi^- \) mass spectra we use the same fit function as described above. The \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) parameters are fixed to the values in Table [1].

| State         | Yield   | M, MeV/c^2 | \( \Gamma \), MeV |
|---------------|---------|------------|-------------------|
| \( \Lambda_c(2880)^+ \) | 690 \pm 50 | 2881.2 \pm 0.2 \pm 0.4 | 5.8 \pm 0.7 \pm 1.1 |
| \( \Lambda_c(2940)^+ \) | 220^{+80}_{-60} | 2938.0 \pm 1.3^{+1.20}_{-1.10} | 13.5 \pm 5.7 |

TABLE I: Signal yield, mass and width for the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \). The first uncertainty is statistical, the second one systematic.
The $\Lambda_c(2880)^+$ yield as a function of $M(\Lambda^+_c\pi^\pm)$ is shown in Fig. 2. We find a clear signal for the $\Sigma_c(2455)$ and an excess of events in the region of the $\Sigma_c(2520)$. We perform a $\chi^2$ fit to the $\Lambda^+_c\pi^\pm$ mass spectrum of Fig. 2 to extract the yields of the $\Sigma_c(2455)$ and $\Sigma_c(2520)$. The fitting function is a sum of three components: $\Sigma_c(2455)$ signal, $\Sigma_c(2520)$ signal and a non-resonant contribution. The $\Sigma_c(2455)$ and $\Sigma_c(2520)$ signals are parameterized by a P-wave Breit-Wigner function convolved with the detector resolution functions, determined from MC ($\sigma = 0.9\,\text{MeV}/c^2$ for the $\Sigma_c(2455)$ and $\sigma = 1.5\,\text{MeV}/c^2$ for the $\Sigma_c(2520)$). The mass and width of the $\Sigma_c(2455)$ are floated, while the mass and width of the $\Sigma_c(2520)$ are fixed to the world average values [5]. The shape of the non-resonant contribution is determined from MC assuming a uniform distribution of the signal over phase space. The fit is shown in Fig. 2. We find the ratios of $\Lambda_c(2880)^+$ partial widths $\frac{\Gamma(\Sigma_c(2455)\pi^\pm)}{\Gamma(\Lambda^+_c\pi^\pm\pi^-)} = 0.404 \pm 0.021 \pm 0.014$, $\frac{\Gamma(\Sigma_c(2520)\pi^\pm)}{\Gamma(\Lambda^+_c\pi^\pm\pi^-)} = 0.091 \pm 0.025 \pm 0.010$ and $\frac{\Gamma(\Sigma_c(2520)\pi^\pm)}{\Gamma(\Sigma_c(2455)\pi^\pm)} = 0.225 \pm 0.062 \pm 0.025$, where the uncertainties are statistical and systematic, respectively. The $\Sigma_c(2455)$ parameters determined from the fit $M = (2453.7 \pm 0.1)\,\text{MeV}/c^2$ and $\Gamma = (2.0 \pm 0.2)\,\text{MeV}$ are consistent with the world average values [6]. The normalized $\chi^2$ of the fit is $\chi^2/d.o.f. = 106.6/75$. The significance of the $\Sigma_c(2520)$ signal is 3.7 standard deviations.

To estimate the systematic uncertainties on the ratios of $\Lambda_c(2880)^+$ partial widths we vary the $\Lambda_c(2880)^+$ parameters, fit interval and background parameterization in the fit to the $M(\Lambda^+_c\pi^\pm\pi^-)$ spectrum; we vary the $\Sigma_c(2520)$ parameters; we allow the shape of the non-resonant contribution to float in the fit, parameterizing it with a second-order polynomial multiplied by a threshold function or by a third-order polynomial; we take into account the uncertainty in the detector resolution and in the reconstruction efficiency. None of the variations reduces the significance of the $\Sigma_c(2520)$ signal below three standard deviations.

To perform angular analysis of $\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^0\pi^+\pi^-\pi^+$ decays we fit the $\Lambda^+_c\pi^+\pi^-$ spectrum in $\cos\theta$ and $\phi$ bins for the $\Sigma_c(2520)$ signal region and sidebands. Here, $\phi$ is the angle between the $e^+e^- \rightarrow \Lambda_c(2880)^+X$ reaction plane and the plane defined by the pion momentum and the $\Lambda_c(2880)^+$ boost direction in the rest frame of the $\Lambda_c(2880)^+$. Figure 3 shows the yield of $\Lambda_c(2880)^+$ as a function of $\cos\theta$ and $\phi$, after $\Sigma_c(2520)$ sideband subtraction (to account for nonresonant $\Lambda^+_c\pi^+\pi^-$ decays) and efficiency correction.

![Figure 2](image2.png)

**FIG. 2:** The $\Lambda_c(2880)^+$ yield as a function of $M(\Lambda^+_c\pi^\pm)$. The histogram represents the result of the fit.

![Figure 3](image3.png)

**FIG. 3:** The yield of $\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^0\pi^+\pi^-\pi^+$ decays as a function of $\cos\theta$ and $\phi$. The fits are described in the text.

The parameterization of $\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)\pi$ decay angular distributions depends on the spin of the $\Lambda_c(2880)^+$. For the spin $\frac{1}{2}$ hypothesis both $\cos\theta$ and $\phi$ distributions are expected to be uniform [10]. $\chi^2$ fits to a constant are shown in Fig. 3 by a dotted line. The agreement is good for $\phi$: $\chi^2/d.o.f. = 5.3/9$, but poor for $\cos\theta$: $\chi^2/d.o.f. = 46.7/9$.

The angular distribution for the spin $\frac{3}{2}$ hypothesis
is \[ W_{3/2} = \frac{3}{4\pi}[\rho_{33} \sin^2 \theta + \rho_{11}(\frac{1}{3} + \cos^2 \theta) - \frac{2}{\sqrt{3}} \text{Re}\rho_{31}(\sin 2\theta - \frac{2}{\sqrt{3}} \text{Re}\rho_{31}\sin 2\theta\cos \phi)], \]

where \( \rho_{ij} \) are the elements of the production density matrix. The diagonal elements are real and satisfy \( 2(\rho_{33} + \rho_{11}) = 1 \). Since the measured distribution in \( \phi \) is consistent with being uniform (this also holds separately for \( \cos \theta > 0 \) and \( \cos \theta < 0 \) samples), the non-diagonal elements are small. The result of the fit to the \( \cos \theta \) spectrum for the spin \( \frac{3}{2} \) hypothesis is shown in Fig. 3 with a solid curve. The agreement is poor: \( \chi^2 / d.o.f. = 35.1 / 8 \).

The angular distribution for the spin \( \frac{3}{2} \) hypothesis is \[ W_{3/2} = \frac{3}{8}(\rho_{55}2(5\cos^4 \theta - 2\cos^2 \theta + 1) + \rho_{33}(15\cos^4 \theta + 14\cos^2 \theta + 1) + 5(1 - \cos^2 \theta)^2), \]

where non-diagonal elements are ignored. The result of the fit to the \( \cos \theta \) spectrum for the spin \( \frac{3}{2} \) hypothesis is shown in Fig. 3 with a solid curve. The agreement is good: \( \chi^2 / d.o.f. = 12.1 / 7 \). We find \( \rho_{55} = 0.09 \pm 0.02 \) and \( \rho_{33} = 0.00 \pm 0.03 \). Thus the \( \Lambda_c(2880)^+ \) populates mainly the helicity \( \frac{1}{2} \) states, \( 2\rho_{11} - 2\rho_{33} - 2\rho_{55} = 0.82 \pm 0.05 \).

The \( \chi^2 \) difference of the spin \( \frac{1}{2} (\frac{3}{2}) \) and spin \( \frac{3}{2} \) fits is distributed as \( \chi^2 \) with two degrees (one degree) of freedom, therefore the exclusion level of the spin \( \frac{3}{2} \) (\( \frac{5}{2} \)) hypothesis is 5.5 (4.8) standard deviations.

To estimate the systematic uncertainty in the angular analysis of the \( \Lambda_c(2880)^+ \rightarrow \Sigma_c(2550)^{0,+,+,-} \) decay we vary the \( \Lambda_c(2880)^+ \) parameters, fit interval and background parameterization in the fit to the \( M(\Lambda^+_c \pi^+ \pi^-) \) spectrum. None of the variations alters the exclusion level of the spin \( \frac{3}{2} (\frac{5}{2}) \) hypothesis to less than 5.5 (4.5) standard deviations.

The Capstick-Isgur quark model predicts the lowest \( J^P = \frac{5}{2}^- \) \( \Lambda_c^+ \) state at 2900 MeV/c\(^2\) and the lowest \( J^P = \frac{3}{2}^+ \) \( \Lambda_c^+ \) state at 2910 MeV/c\(^2\). The typical accuracy of quark model predictions is 50 MeV/c\(^2\), therefore the agreement with the experimental value for the \( \Lambda_c(2880)^+ \) mass is quite good. The lowest spin \( \frac{5}{2} \) states are well separated from the next \( J = \frac{3}{2} \) levels (3130 MeV/c\(^2\) for negative and 3140 MeV/c\(^2\) for positive parities) and from \( J = \frac{1}{2} \) levels (3125 MeV/c\(^2\) for negative and 3175 MeV/c\(^2\) for positive parities).

Heavy Quark Symmetry predicts \( R \equiv \frac{\Gamma(\Sigma_c(2520)\pi^+)}{\Gamma(\Sigma_c(2455)\pi^+)} = 1.4 \) for the \( \frac{3}{2}^- \) state and \( R = 0.23 - 0.36 \) for the \( \frac{5}{2}^+ \) state [6, 17]. The measured value \( R = 0.225 \pm 0.062 \pm 0.025 \) favors the positive parity assignment for the \( \Lambda_c(2880)^+ \).

The \( \frac{5}{2}^- \) assignment for the \( \Lambda_c(2880)^+ \) makes it a special state that lies on the leading \( \Lambda_c^+ \) Regge trajectory, whose lower \( J^P \) members are the \( \frac{1}{2}^+ \Lambda_c^+ \) and \( \frac{3}{2}^- \Lambda_c(2625)^+ \). The \( \frac{5}{2}^- \) assignment for the \( \Lambda_c(2880)^+ \) based on a string model for baryons was proposed in Ref. [18].

In summary, from angular analysis of \( \Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^{0,+,+,-} \) decays we find that a \( \Lambda_c(2880)^+ \) spin hypothesis of \( \frac{5}{2}^- \) is strongly favored over \( \frac{3}{2}^- \) and \( \frac{3}{2}^+ \). We find first evidence for \( \Sigma_c(2520)\pi \) intermediate states in the \( \Lambda_c(2880)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^- \) decays and measure \( \Gamma(\Sigma_c(2520)\pi^+) = 0.225 \pm 0.062 \pm 0.025 \). This value is in agreement with Heavy Quark Symmetry predictions and favors the \( \frac{5}{2}^- \) over the \( \frac{3}{2}^- \) hypothesis for the spin-parity of the \( \Lambda_c(2880)^+ \). We also report the first observation of \( \Lambda_c(2940)^+ \rightarrow \Sigma_c(2455)\pi \) decays, and measure the \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) parameters.

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