Measurement of the masses and widths of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ baryons

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Using 980 fb^{-1} of data collected with the Belle detector operating at the KEKB asymmetric-energy e^+e^- collider, we report the measurements of the masses, and the first measurements of the instrinsic widths, of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ charmed baryons. We find $M(\Sigma_c(2455)^+) - M(\Lambda_c^+) = 166.17 \pm 0.05^{+0.16}_{-0.07}$ MeV/c^2, $\Gamma(\Sigma_c(2455)^+) = 2.3 \pm 0.3 \pm 0.3$ MeV/c^2, $M(\Sigma_c(2520)^+) - M(\Lambda_c^+) = 230.9 \pm 0.5^{+0.5}_{-0.1}$ MeV/c^2, and $\Gamma(\Sigma_c(2520)^+) = 17.2^{+2.3+3.1}_{-2.1-0.7}$ MeV/c^2, where the uncertainties are statistical and systematic, respectively. These measurements can be used to test models of the underlying quark structure of the Σ_c states.

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I. INTRODUCTION

The Σ_c charmed baryons consist of a charm quark in combination with a spin-1 light (uu, ud or dd) diquark. The lowest of these states are the $\Sigma_c(2455)$ isotriplet which have $J^P = \frac{1}{2}^+$, with the next most massive being the $J^P = \frac{3}{2}^+$ $\Sigma_c(2520)$ isotriplet. All these six states decay strongly to $\Lambda_c^+\pi$. The doubly charged and neutral states, both of which decay with the emission of a charged pion, have been well studied. The most precise measurements of their masses and widths have been made [1] by the Belle Collaboration using the same dataset as the analysis presented here. However, π^0 transitions have lower efficiency, higher backgrounds and inferior resolution to $\pi^\pm$ transitions, so there is comparatively little experimental information on the singly charged Σ_c^+ states [2].

All mass measurements of the Σ_c baryons have been made with respect to the Λ_c^+ mass, as the resolution of these mass differences [denoted $\Delta(M)$] is superior to that of the individual baryons. The CLEO Collaboration has measured $\Delta(M)$ for both the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ states [3] but were only able to set limits on their intrinsic widths. The large Belle dataset allows for much more precise measurements of the masses of these particles than has been possible hitherto and also the first measurements of their widths.

Measurements of the masses of all members of the two isotriplets allow tests of models of isospin mass splittings. In the model of Yang and Kim [4], for instance, the mass splittings from the following four sources add: the electromagnetic corrections due to the light quarks, the differences of the masses of the u and d quarks, the hyperfine interactions between the light quarks, and the Coulomb interactions between the soliton and charm quark. Most mass models predict that the singly charged states should have masses a little lower than their doubly charged and neutral analogs [5], and this is true in the limited precision measurements made to date [6].

The natural width of the $\Sigma_c(2455)^+$ is predicted to be somewhat larger than its isospin partners; this is mostly because of the effect of the $\pi^\pm/\pi^0$ mass difference on the available phase space for the decay. There is also a possibility that electromagnetic decays are non-negligible. Cheng and Chua [7] predict $\Gamma(\Sigma_c(2455)^+) = 2.3^{+0.1}_{-0.2}$ MeV/c^2 using the experimental value of $\Gamma(\Sigma_c(2455)^{++}) = 1.94^{+0.08}_{-0.16}$ MeV/c^2 as input. For the $\Sigma_c(2520)$, it is expected that the instrinsic width of the Σ_c^+ will be similar to those measured for its isospin partners of $\Gamma(\Sigma_c(2520)^{++}) = 14.8^{+0.3}_{-0.4}$ MeV/c^2 and $\Gamma(\Sigma_c(2520)^0) = 15.3^{+0.4}_{-0.5}$ MeV/c^2, respectively; the two effects listed above are expected to be small compared with these values.

In addition to checking the quark model predictions, the parameters of the $\Sigma_c(2455)^+$ are vital in studies of the $\Lambda_c(2595)^+$, whose pole mass appears to be between the $\Sigma_c(2455)^+\pi^0$ and $\Sigma_c(2455)^{++}\pi^-$ thresholds. This particle, although generally considered to be an orbitally excited heavy-quark light-diquark state, has been conjectured to have different underlying quark structure [8]. The threshold behavior, and thus measurement of the pole mass and width, of the $\Lambda_c(2595)^+$ is critically dependent on the masses and widths of the Σ_c particles.

II. DETECTOR AND DATASET

This analysis uses a data sample of e^+e^- annihilations recorded by the Belle detector [9] operating at the KEKB asymmetric-energy e^+e^- collider [10]. It corresponds to an integrated luminosity of 980 fb^{-1}. The majority of these data were taken with the accelerator energy tuned for production of the $\Upsilon(4S)$ resonance, as this is optimum for investigation of B decays. However, the Σ_c particles in this analysis are produced in continuum charm production and are of higher momentum than those that are decay products of B mesons. This allows the use of the complete Belle dataset which includes data taken at beam energies corresponding to the other Υ resonances and the nearby continuum. The Belle detector is a large solid-angle spectrometer comprising six subdetectors: the silicon vertex detector (SVD), the 50-layer central drift chamber (CDC), the aerogel Cherenkov counter (ACC), the time-of-flight scintillation counter (TOF), the electromagnetic calorimeter (ECL), and the K_L and muon detector. A superconducting solenoid produces a 1.5 T magnetic field throughout the first five of these subdetectors. The detector is described in detail elsewhere [9]. Two inner detector configurations were used. The first comprised a 2.0 cm radius beampipe and a three-layer silicon vertex detector, and the second a 1.5 cm radius beampipe and a four-layer silicon detector and a small-cell inner drift chamber.

III. ANALYSIS

We study Σ_c^+ baryons from the decay chain $\Sigma_c^+ \to \Lambda_c^+\pi^0, \Lambda_c^+ \to pK^-\pi^+$. The decays are reconstructed from combinations of charged particles measured using the tracking system, and neutral particles measured in the ECL. Final-state charged particles, π^+, K^-, and p, are selected using the likelihood information from the tracking (SVD, CDC) and charged-hadron identification (CDC, ACC, TOF) systems into a combined likelihood, $\mathcal{L}(h1{:}h2) = \mathcal{L}_{h1}/(\mathcal{L}_{h1}+\mathcal{L}_{h2})$ where $h1$ and $h2$ are p, K, and π as appropriate [11]. We require proton candidates to have $\mathcal{L}(p{:}K) > 0.6$ and $\mathcal{L}(p{:}\pi) > 0.6$, kaon candidates to have $\mathcal{L}(K{:}p) > 0.6$ and $\mathcal{L}(K{:}\pi) > 0.6$, and pions to have requirements of $\mathcal{L}(\pi{:}K) > 0.6$ and $\mathcal{L}(\pi{:}p) > 0.6$. The efficiencies of these hadron identification requirements are about 90%, 90%, and 93% for pions, kaons and protons, respectively. The probability to misidentify a pion (kaon) track as a kaon (pion) track is about [9 (10)]%, and the momentum averaged probability to misidentify a pion or kaon track as a proton track is about 5%. Combinations of $pK^-\pi^+$ candidates with an invariant mass within 3.9 MeV/c^2 [approximately 2 standard deviations (σ)] of the Λ_c^+ were retained as Λ_c^+ candidates. The number of events having more than one Λ_c^+ candidate which share a daughter particle is approximately 1%.

The π^0 candidates are reconstructed from two detected neutral clusters in the ECL each consistent with being due to a photon and each with an energy greater than 50 MeV in the laboratory frame. The invariant mass of the photon pair is required to be within 5.4 MeV/c^2 ($\approx 2\sigma$) of the nominal π^0 mass. The two photons are then constrained to this mass to improve the momentum resolution of the π^0.

To optimize the requirements specific to this analysis, a simulated data set is constructed using a combination of the decays under study and e^+e^- hadronic events generated by PYTHIA [12]. We find that the following requirements are optimal for the highest $\Sigma_c(2455)^+$ signal significance: the momentum of the Σ_c^+ candidate in the e^+e^- center-of-mass frame, $p^* > 2.6$ GeV/c; the momentum of the π^0 in laboratory frame, $p > 200$ MeV/c.

The Monte Carlo (MC) simulation is performed using a GEANT-based MC simulation [13] to model the response of the detector. The photon energy response in the simulation is corrected to take into account the data-MC difference of resolution based on studies of mass resolution in the decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $D^{*0} \to D^0\gamma$ [14,15]. The resolution of the $\Sigma_c(2455, 2520)^+$ mass peaks is parametrized by double-Gaussian resolution functions with a small offset in the peak mass allowed. The parameters of these functions are shown in Table I, and the statistical uncertainties in these values are negligible. It is immediately clear that knowledge of the $\Sigma_c(2455)^+$ signal resolution is vital as it is similar to the expected intrinsic width. To further check the MC simulation, a study was made of the decay $D^{*+} \to D^+\pi^0$, where $D^+ \to K^-\pi^+\pi^+$. This decay has almost the same final state as the one under consideration,

TABLE I. Parameters of the double-Gaussian resolution function derived from the Monte Carlo program.

Particle	$\sigma_{\mathrm{narrow}}(\mathrm{MeV}/c^2)$	$\sigma_{\mathrm{wide}}(\mathrm{MeV}/c^2)$	$\mathrm{Area}_{\mathrm{wide}}/\mathrm{Area}_{\mathrm{narrow}}$	Mass offset (MeV/c^2)
$\Sigma_c(2455)^+$	1.473	2.932	0.97	0.078
$\Sigma_c(2520)^+$	2.23	4.22	3.06	0.08

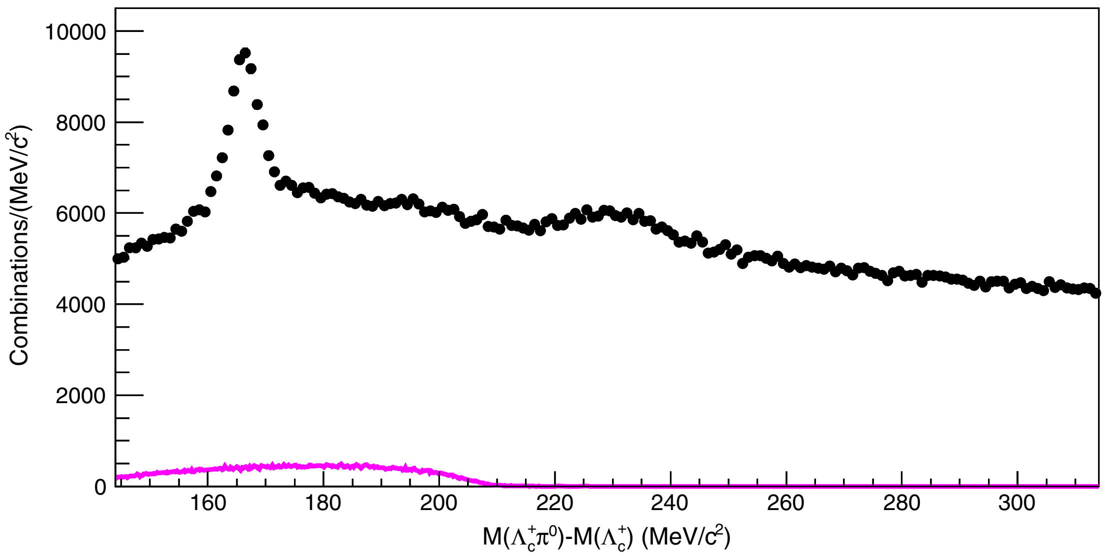

FIG. 1. The mass difference $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ for the entire mass range of interest. The line shows the expected contribution from $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^0\pi^0$ decays assuming uniform three-body phase-space.

similar momentum distribution, is much more copiously produced, and has a very small and well-known intrinsic width. The resolution of this mode is found to be 3% larger in data than in MC simulations, and the reconstructed mass was found to be $0.020 \pm 0.015\ \mathrm{MeV}/c^2$ lower, where the uncertainty is due to the Particle Data Group value [6] as our statistical uncertainties are negligible. We take these comparisons into account in the considerations of the systematic uncertainties of our Σ_c^+ measurements.

Figure 1 shows the invariant mass distribution for the $\Lambda_c^+\pi^0$ candidates. Clear signals are seen corresponding to $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ production. In addition, we see the large enhancement up to a mass difference of $\approx 200\ \mathrm{MeV}/c^2$ due to $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^0\pi^0$ decays as they produce $\Lambda_c^+\pi^0$ combinations with mass differences up to the kinematic limit of $M(\Lambda_c^+(2625)) - M(\Lambda_c^+) - M(\pi^0) = 207\mathrm{MeV}/c^2$. The simulated shape of this component is shown in Fig. 1. There is also a possible enhancement due to $\Lambda_c(2625)^+ \to \Sigma_c^+\pi^0$ decays that may produce an enhancement at around $194\ \mathrm{MeV}/c^2$. These enhancements were anticipated because of isospin symmetry, but these particular decays have never been studied. The "cusp" behavior at around $200\ \mathrm{MeV}/c^2$ is particularly problematic as its shape depends on the relative contributions of three-body decays, decays proceeding through virtual $\Sigma_c(2520)$ production, and the interference between these two [16]. Rather than fitting the entire spectrum, we decided to find the signal parameters from fits performed to limited-range subsets of this data which do not include this cusp region. These are shown in Fig. 2 and Fig. 3 for the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ regions, respectively. The results of a global fit to Fig. 1 will be taken into account in the systematic uncertainty determination.

A fit is made to Fig. 2 using a third-order Chebychev polynomial function to represent the background, and a P-wave relativistic Breit-Wigner function convolved with the previously described double-Gaussian resolution function, taking into account the small mass offset. The Breit-Wigner signal function includes a Blatt-Weisskopf barrier factor [17], with the radius parameter of $R = 3\ \mathrm{GeV}^{-1}$ [18]. The results of this fit are a mass difference of $\Delta(M) = 166.17 \pm 0.05\ \mathrm{MeV}/c^2$ and $\Gamma = 2.3 \pm 0.3\ \mathrm{MeV}/c^2$. The fit is made using a maximum-likelihood method to a large number of

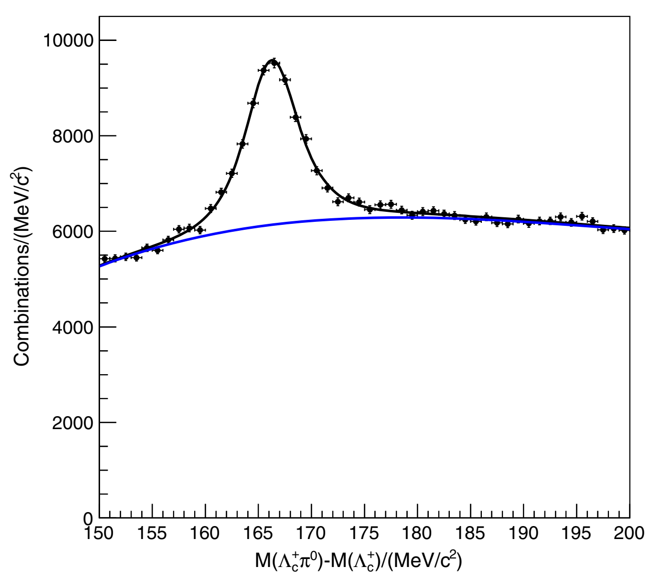

FIG. 2. The mass difference $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ in the region of the $\Sigma_c(2455)^+$. The fit to the data is described in the text, and the lower line shows its contribution from the background function.

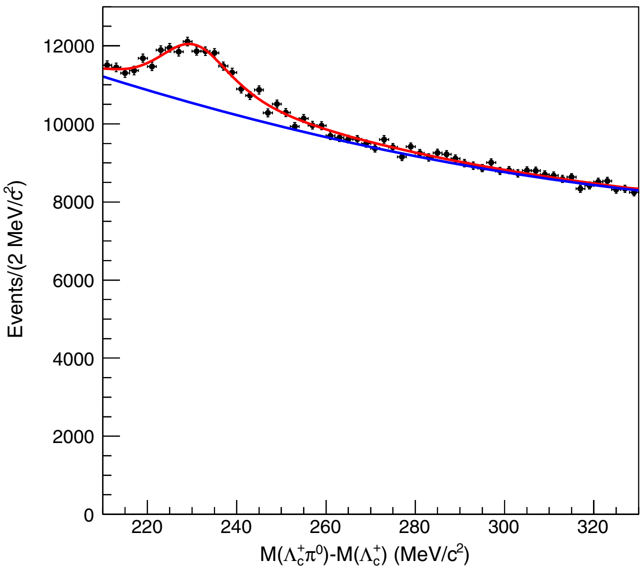

FIG. 3. The mass difference $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ in the region of the $\Sigma_c(2520)^+$. The fit to the data is described in the text, and the lower line shows its contribution from the background function.

small bins so that any uncertainty due to bin size is negligible. A convenient test of the goodness-of-fit is the χ^2 per degree of freedom (reduced χ^2) for the distribution as shown, and for Fig. 2 this reduced χ^2 is $49.2/43 = 1.14$.

A fit is made to Fig. 3 using a second-order Chebychev polynomial function to represent the background, and a P-wave relativistic Breit-Wigner function convolved with the double-Gaussian resolution function described above. The results of this fit are a mass difference of $\Delta(M) = 230.9 \pm 0.5\ \mathrm{MeV}/c^2$ and $\Gamma = 17.2^{+2.3}_{-2.1}\ \mathrm{MeV}/c^2$. The reduced χ^2 of the fit for the plot as shown is $52.8/44 = 1.20$.

IV. SYSTEMATIC UNCERTAINTIES

In all four measurements, we take the systematic uncertainty due to fitting as the maximum variation of the measured parameters using different fitting functions which produce acceptable fits to the data. For the $\Sigma_c(2455)^+$ we vary the power of the polynomial background function from 2 to 4, allow the possibility of a satellite peak due to $\Lambda_c(2625)^+ \to \Sigma_c^+\pi^0$ decays as such decays are expected at a low level, investigate the changes in parameters with small changes to the fitting ranges, and also compare the results of the fit shown in Fig. 2 with the results of a global fit to Fig. 1 which includes contributions from $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ decays.

The differences in the values obtained using reasonable variations of the Blatt-Weisskopf barrier parameter, R, were found to be small. As the measurement of the D^{*+} width indicates a possible underestimation of the detector resolution by 3%, we also perform a fit using a resolution 6% higher than that found from MC simulations and conservatively take the change in the parameters as the systematic uncertainty arising from the uncertainty in the mass resolution. We similarly study the variation of the $\Sigma_c(2520)^+$ measured parameters to estimate the associated systematic uncertainties, but here we cannot reduce the order of the polynomial background function as a first order polynomial does not produce a satisfactory fit to the data.

TABLE II. Contributions to the systematic uncertainties of the mass difference and width measurements of the two states in MeV/c^2.

	$\Sigma_c(2455)^+$		$\Sigma_c(2520)^+$	
	$\Delta(M)$	Γ	$\Delta(M)$	Γ
Background function	$^{+0.00}_{-0.07}$	$^{+0.30}_{-0.04}$	$^{+0.4}_{-0.0}$	$^{+3.0}_{-0.5}$
Signal function	$^{+0.06}_{-0.01}$	$^{+0.01}_{-0.33}$	$^{+0.0}_{-0.1}$	$^{+0.7}_{-0.5}$
Photon energy scale	$^{+0.15}_{-0.00}$	$^{+0.00}_{-0.00}$	$^{+0.3}_{-0.0}$	$^{+0.0}_{-0.0}$

For the systematic uncertainty due to the energy scale, we allow for the possibility that the D^{*+} mass is measured up to $0.035\ \mathrm{MeV}/c^2$ lower than the true mass. We make the conservative assumption that the difference between the measured and canonical masses of the D^{*+} is entirely due to a miscalibration of our photon energy scale and use MC simulation to estimate how a change in the D^{*+} mass, which is a decay with a very small four-momentum-squared (q^2) associated with it, translates to a change in mass for a particle decaying with a larger q^2. The result of this study is a possible upward shift of $0.15\ \mathrm{MeV}/c^2$ in the mass of the $\Sigma_c(2455)^+$ and $0.3\ \mathrm{MeV}/c^2$ for the $\Sigma_c(2520)^+$. The systematic uncertainty estimations are tabulated in Table II.

V. DISCUSSION

The measured intrinsic widths are consistent with the quark model predictions [7], namely that it is the same as the widths of their isospin partners, except for a small change due to the increased phase-space available. The measured mass differences are consistent with, but more precise than, the previous measurements [6] and confirm the picture in which the singly charged states are slightly lower in mass than their isospin partners. According to the model first proposed by Franklin [19] the value of the mass relationship $M(\Sigma_c^{++}) + M(\Sigma_c^0) - 2 \times M(\Sigma_c^+)$ should be the same for the $\Sigma_c(2455)$ and $\Sigma_c(2520)$ isotriplets. Combining our measurements for the singly charged Σ_c states with those of the Particle Data Group [6] for the others, we find values of $2.46^{+0.17}_{-0.34}$ and $2.2^{+1.0}_{-1.4}\ \mathrm{MeV}/c^2$ for the two systems, respectively, consistent with the model. Yang and Kim [4] further predict the mass difference between the singly charged and neutral Σ_c baryons should be the same as those between the analogous Ξ_c' and Ξ_c^* states, and our results are also consistent with this prediction.

VI. CONCLUSIONS

We measure the mass difference of the $\Sigma_c(2455)^+$ with respect to the Λ_c^+ to be $\Delta(M) = 166.17 \pm 0.05^{+0.16}_{-0.07}$ MeV$/c^2$ and its intrinsic width $\Gamma = 2.3 \pm 0.3 \pm 0.3$ MeV$/c^2$. For the $\Sigma_c(2520)^+$ the analogous values are $\Delta(M) = 230.9 \pm 0.5^{+0.5}_{-0.1}$ MeV$/c^2$ and $\Gamma = 17.2^{+2.3+3.1}_{-2.1-0.7}$ MeV$/c^2$. These are the first nonzero measurements of the intrinsic widths of these particles and show no deviation from the expectations based upon the precise measurements of their isospin partners made using the standard quark model.

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