First Measurement of the $\Lambda_c^+ \rightarrow P + \eta'$ Decay

Physics 684 Presentation

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Motivation

Decays of charmed baryons provide a laboratory to understand the interplay of weak and strong interactions in charm system.

The decay of these baryons can be used then to test various models and assumptions, such as $SU(3)_f$ symmetry or the constituent quark model.

The Λ_c^+ Baryon and η' Meson

The charmed baryon under investigation in this paper is the Λ_c^+ baryon. This particle decays into a wide range secondary particles. For this investigation, the decay of the $\Lambda_c^+ \to P + \eta'$

$$\eta_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \tag{1}$$

$$\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \tag{2}$$

$$\begin{pmatrix} \cos\theta_p & -\sin\theta_p \\ \sin\theta_p & \cos\theta_p \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_1 \end{pmatrix} = \begin{pmatrix} \eta \\ \eta' \end{pmatrix} \tag{3}$$

To avoid theoretical difficulties in the factorization approach, one can relate the amplitudes among different decays using $SU(3)_F$ flavor symmetry, or other theoretical approaches (Constituent Quark Model.)

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\eta')}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

The $\Lambda_c^+ \to P + \eta'$ decay to be compared to is the $\Lambda_c^+ \to P + K^- + \pi^+$, which has a known $\beta(\Lambda_c^+ \to P + K^- + \pi^+)$.

Models

Until recently, this specific decay had not been observed. Theoretical predictions for the singly Cabibbo-suppressed decay of Λ_c^+ baryon were predicted as follows.

	$SU(3)_F$ symmetry [5]	$SU(3)_F$ symmetry [13]	Constituent quark model [3]
$\mathcal{B}(\Lambda_c^+ \to p\eta')$	$0.4 - 0.6$	$1.22^{+1.43}_{-0.87}$	$0.04 - 0.2$

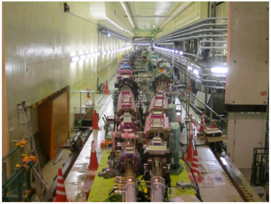
The units of these predictions are in 10^{-3}. As one can see, the ranges of the $SU(3)_f$ predictions and the constituent quark model predictions do not overlap with each other.

The KEKB Accelerator and Belle Detector

The KEKB is a particle accelerator located in Tsukuba, Japan. It was built to study CP violation in the Belle experiment. It was upgraded in 2018 to the SuperKEKB. The Belle detector was also upgraded to the Belle II detector around the same time.

The KEKB accelerator is also know as the B-factory, as it operates at a center of mass energy of 10.58GeV, which is ideal for producing large amounts of B mesons.

Figure: Tsukuba Japan and a portion of the SuperKEKB Accelerator



The KEKB Accelerator and Belle Detector

The KEKB accelerator is an electron - positron collider. A linear accelerator is used to produce a beam of electrons, some of which interact with a Tungsten target to produce a beam of positrons.

The positrons are sent to a dampening ring (DR) before sent into the LER (low energy ring). The electrons travel into the HER (high energy ring).

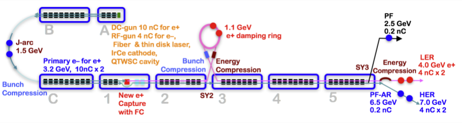


Figure: A Diagram of the KEKB LINAC

The KEKB Accelerator and Belle Detector

The LINAC transports the electron beam and the positron beam into two ring accelerators, each with a circumference of roughly 3020 meters. The beams have a single meeting point in the Belle II detector in the Tsukuba section of the collider.

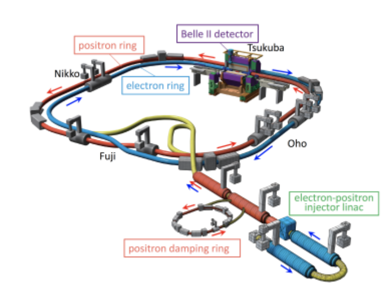


Figure: A Diagram of the KEKB Collider

The KEKB Accelerator and Belle Detector

The Belle detector is a large-solid-angle magnetic spectrometer that consists of multiple particle detection systems.

- SVD - Silicon Vertex Detector
- CDC - Central Drift Chamber
- ACC - Aerogel Threshold Cherenkov Counters
- TOF - Time-of-Flight Scintillation Counters
- ECL - Electronic Calorimeter

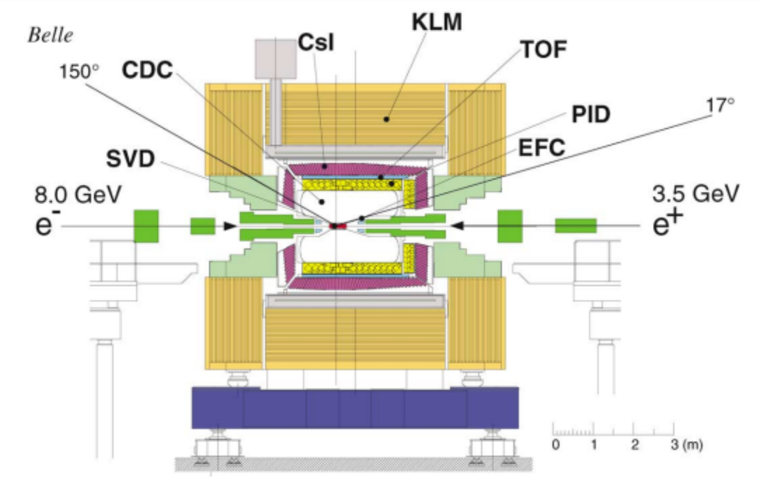


Figure: A Diagram of the Belle Detector

Monte Carlo Simulation

Monte Carlo simulated events were used to optimize the selection criteria, study backgrounds, and determine the signal reconstruction efficiency.

- Signal events were simulated in EVTGEN, and propagated through the detector simulation based on GEANT3.
- The $e^+e^- \to c\bar{c}$ events were simulated with PYTHIA.
- The $\Lambda_c^+ \to P + K^- + \pi^+$ and $\eta' \to \eta + \pi^+ + \pi^-$ events were simulating using a phase space model.
- The effect of final-state radiation from charged particles is simulated in the PHOTOS package.

Events were simulated for $\Upsilon(1S, 2S, 3S, 4S, 5S)$ resonances.

Selection Criteria

Overleaf

Selection criteria are optimized my maximizing a figure-of-merit equation,

$$FOM = \frac{\epsilon}{\left(\frac{a}{2} + \sqrt{n_B}\right)} \tag{4}$$

where a is selected as 5, and n_B is the expected number of background events in a two-dimensional signal region of η' and Λ_c^+ signals.

Selection Criteria

Decays of $\Lambda_c^+ \to P + \eta'$ and $\Lambda_c^+ \to P + K^- + \pi^+$ are reconstructed, with the η' decay reconstructed in the cascade $\eta + \pi^+ + \pi^-$, $\eta \to \gamma + \gamma$.

Final-state charged tracks are identified as p, K, or π candidates using information from the charged-hadron identification systems (ACC, TOF, CDC).

$$R(h|h') = \frac{L(h)}{(L(h) + L(h'))} \tag{5}$$

Information from the ACC, CDC, and ECL is used to make R(e). These likelihood ratios are used to compute identification efficiencies of p, K, and π.

Selection Criteria

η candidates are reconstructed via their decay into two protons, which are identified by ECL clusters not associated with any charged tracks. The $\gamma + \gamma$ invariant mass is required to be between 0.45 GeV/c^2 and 0.65 GeV/c^2.

To further suppress background events, events, η candidates in which either daughter photons can be combined with other photons in the event to form $\pi^0 \rightarrow \gamma + \gamma$. This rejected 42 percent of the background, while retaining 83 percent of the signal.

Selection Criteria

The η' candidates were reconstructed by combining two oppositely charged π tracks with an η candidate.

After the preliminary selection, about 0.8% of the $\Lambda_c^+ \to P + K^- + \pi^+$ events and 13.3% of the $\Lambda_c^+ \to P + \eta'$ events had two or more Λ_c^+ candidates.

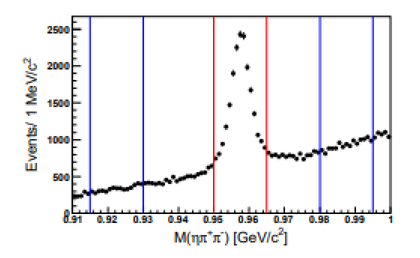
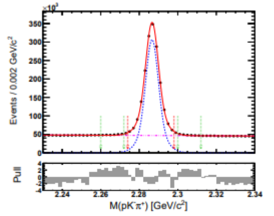
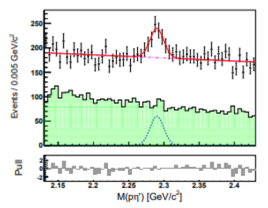


Figure: Invariant mass distribution for $\eta + \pi^+ + \pi^-$.

Signal and Background Estimation

With the selection criteria applied, the invariant mass distributions of normalized and signal modes are found. From the study of generic Monte Carlo Samples, no known peaking background processes contribute to mass distributions in the Λ_c^+ signal region.





Signal and Background Estimation

To extract the number of signal events, a unbinned maximum-likelihood fit was applied to the M($P+K^-+\pi^-$) and M($P+\eta'$) distributions. The likelihood function is defined in terms of the signal PDF (F_S) and the background PDF (F_B). N is the total number of observed events, n_S and n_B are the numbers of signal events and background events, and M is the invariant mass.

$$\mathcal{L} = \frac{e^{-(n_{\mathrm{S}}+n_{\mathrm{B}})}}{N!} \prod_{i}^{N} [n_{\mathrm{S}} F_{\mathrm{S}}(M_i) + n_{\mathrm{B}} F_{\mathrm{B}}(M_i)]$$

Figure: Likelihood Equation

Signal and Background Estimation

For the $\Lambda_c^+ \rightarrow P + K^- + \pi^-$ channel, the Λ_c^+ signal yields are extracted by fitting the M($P + K^- + \pi^+$) distribution. N_{norm} was found to be 1472190 +/- 5726, where the uncertainty is statistical. The mass resolution (from the Monte Carlo simulation) is 8 MeV/c^2.

For the $\Lambda_c^+ \rightarrow P + \eta'$ channel, the sidebands were checked, but negligible contribution from $\Lambda_c^+ \rightarrow P + \pi^+|\pi^- + \eta$ decays. A Gaussian function and Crystal Ball function was fit to the distribution. N_{sig} = 294 +/- 52, where the uncertainty is statistical. The mass resolution was predicted to be 13 MeV/c^2 from the MC Simulation.

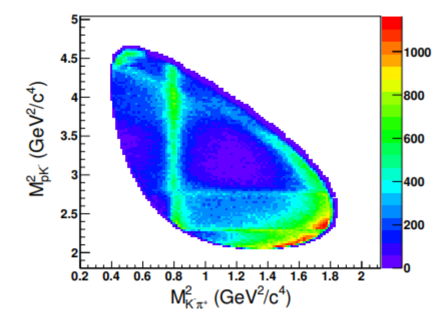
Signal and Background Estimation

To measure the branching fraction, we divide these extracted signal yields by their reconstruction efficiencies.

$\Lambda_c^+ \to P + \eta'$ is a two body decay, and $\eta' \to \eta + \pi^+ + \pi^-$ is well modeled by phase space, so reconstruction efficiency is directly estimated from the simulated events.

However, the reconstruction efficiency for the $\Lambda_c^+ \to P + K^- + \pi^+$ varies across the three-body phase space. To take this into account, the reconstruction efficiency is corrected according to the Dalitz plot.

Signal and Background Estimation



$$\epsilon_{norm}^{correction} = \frac{\sum_i s_i}{\sum_j (\frac{s_j}{\epsilon_j})} \tag{6}$$

Results

$$\frac{\beta(\Lambda_c^+ \to P + \eta')}{\beta(\Lambda_c^+ \to P + K^- + \pi^+)} = \frac{\frac{N_{sig}}{\epsilon_{sig}}}{\frac{N_{norm}}{\epsilon_{norm}^{correction}}} \times \frac{1}{\beta'} \quad (7)$$

$$\beta' = \beta(\eta' \to \eta + \pi^+ + \pi^-) \times \beta(\eta \to \gamma + \gamma) \quad (8)$$

$$\frac{\beta(\Lambda_c^+ \to P + \eta')}{\beta(\Lambda_c^+ \to P + K^- + \pi^+)} = (7.54 + / - 1.32 + / - 0.73) \times 10^{-3} \quad (9)$$

$$\beta(\Lambda_c^+ \to P + \eta') = (4.73 + / - 0.82 + / - 0.46 + / - 0.24) \times 10^{-4} \quad (10)$$

Uncertainties

Source	Systematic uncertainties (%)
PID efficiency	3.5
Photon efficiency	4.0
η' mass window	0.8
Best-candidate selection	1.2
Normalization mode fit	1.8
Signal mode fit	7.6
$\mathcal{B}'$	1.3
Signal MC sample size	0.7
Total	9.7

Figure: Sources of relative systematic uncertainties

Conclusion

Overleaf

	$SU(3)_F$ symmetry [5]	$SU(3)_F$ symmetry [13]	Constituent quark model [3]
$\mathcal{B}(\Lambda_c^+ \to p\eta')$	$0.4 - 0.6$	$1.22^{+1.43}_{-0.87}$	$0.04 - 0.2$

As shown on the previous slides, the results for $\beta(\Lambda_c^+ \to P + \eta')$ was found to be 4.73 +/- 1.52 $\times 10^{-4}$. The significance observed for this decay is 5.4σ. This is consistent with the $SU(3)_f$ predictions, and inconsistent with the constituent quark model prediction.

References

1 The Belle Collaboration, *First Measurement of the* $\Lambda_c^+ \to p\eta'$ *decay*, 2022

2 K.A.K. Furukawa, Haruyo Koiso, SuperKEKB accelerator team, *SuperKEKB Collider*, 2018

3 The Belle Collaboration, *The Belle detector*, 2002