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Observation of the Cabibbo Suppressed Charmed Baryon Decay $\Lambda_c^+ \to p\phi$

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Abstract

We report the observation of the Cabibbo-suppressed decays $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\phi$ using data collected with the CLEO II detector at CESR. The latter mode, observed for the first time with significant statistics, is of interest as a test of color-suppression in charm decays. We have determined the branching ratios for these modes relative to $\Lambda_c^+ \to pK^-\pi^+$ and compared our results with theory.

The strength of color-suppression in internal W-emission charmed meson decays has long been in question. For example, $B(D_s^+ \to \bar{K}^{*0}K^+)/B(D_s^+ \to \phi\pi^+) \simeq 1$ [1, 2], while the expectation from color-matching requirements is that this ratio should be about 1/18. Reasonable overall agreement with the experimental data in the charm sector has been obtained using factorization and taking the large N_c limit in a $1/N_c$ expansion approach, where N_c is the number of quark colors [3, 4]. The Cabibbo-suppressed charmed baryon decay $\Lambda_c^+ \to p\phi$, shown in Figure 1, is also naively expected to be color-suppressed. However, using factorization and taking the limit $N_c \to \infty$ leads to a prediction of no color-suppression [5]. Since the $\Lambda_c^+ \to p\phi$ decay receives contributions only from factorizable diagrams, a reliable calculation should be obtained using factorization. Observation of the $\Lambda_c^+ \to p\phi$ decay was first reported by the ACCMOR collaboration with 2.8 ± 1.9 events [9]. Last year the E687 collaboration published results on the first observation of the Cabibbo-suppressed charmed baryon decay $\Lambda_c^+ \to pK^+K^-$, along with an upper limit on the resonant substructure $\Lambda_c^+ \to p\phi$ [10]. Herein we present new CLEO results on the observation of $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\phi$ decays and discuss the implications of the results.

We use a data sample recorded with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). The sample consists of e^+e^- annihilations taken at and slightly below the $\Upsilon(4S)$ resonance, for a total integrated luminosity of 3.46 fb^{-1}. The main detector components which are important for this analysis are the tracking system and the barrel Time-of-Flight (TOF) particle identification system. Additional particle ID is provided by specific ionization (dE/dx) information from the tracking system's main drift chamber. A more detailed description of the CLEO II detector has been provided elsewhere [11].

To search for the Λ_c^+ signals, we study pK^+K^- track combinations found by the tracking system. The p and $K^\pm$ candidates are identified by combining information from the TOF and dE/dx systems to form a combined χ^2 probability $\mathcal{P}_i$ for each mass hypothesis $i = \pi, K, p$. Using these probabilities $\mathcal{P}_i$, a normalized probability ratio L_i is evaluated for each track according to the formula: $L_i \equiv \mathcal{P}_i/(\mathcal{P}_\pi + \mathcal{P}_K + \mathcal{P}_p)$. Well-identified protons form a sharp peak near $L_p = 1$, while tracks identified as *not* being protons form a peak near $L_p = 0$. The remainder of the candidates fall in the region between 0 and 1. For the proton involved in each decay mode under study, we require $L_p > 0.9$, which constitutes a strong cut. For the kaons, we apply a loose cut of $L_K > 0.1$. In addition, all protons and kaons must pass a minimum requirement of $\mathcal{P}_p > 0.001$ and $\mathcal{P}_K > 0.001$, respectively. In order to reduce the large combinatoric background, the candidate Λ_c^+ scaled momentum $x_p = P_{\Lambda c}/\sqrt{E_{beam}^2 - m_{\Lambda c}^2}$ is limited to $x_p > 0.5$.

The pK^+K^- invariant mass is shown in Figure 2. The broad enhancement in the mass region above 2.37 GeV/c^2 is a reflection from the decay mode $\Lambda_c^+ \to pK^-\pi^+$, where the pion has been misidentified as a kaon. The spectrum is fitted to a Gaussian for the signal with width fixed to $\sigma = 4.9$ MeV/c^2 determined from Monte Carlo simulation [12], and a 2$^{\mathrm{nd}}$ order Chebychev polynomial for the smooth background. This fit yields 214 ± 50 events for the inclusive $\Lambda_c^+ \to pK^+K^-$ signal with a mean mass of 2285.5 ± 1.2 MeV/c^2[13].

To find a $\Lambda_c^+ \to p\phi$ signal, we reconstruct ϕ candidates through their decays $\phi \to K^+K^-$. Because the width of the ϕ is comparable to the detector mass resolution, the ϕ signal shape is best described by a convolution of a Gaussian and a Breit-Wigner of width $\Gamma = 4.43$ MeV/c^2 [1]. The background is parameterized by a function of the form $b(m) = N(m - m_0)^\alpha e^{\beta(m-m_0)}$. The measured Gaussian resolution from the fit is $\sigma = 1.6 \pm 0.2$ MeV/c^2. In order to perform background subtractions, $1.0121 < m_{KK} < 1.0273$ GeV/c^2 is designated as the ϕ "signal" region, while $0.990 < m_{KK} < 1.005$ GeV/c^2 and $1.035 < m_{KK} < 1.050$ GeV/c^2 are designated as the "sideband" regions. Integrating the background function over the sideband and signal regions gives a signal-to-sideband scale factor $R_\phi = 0.560 \pm 0.016$, which is used in the ϕ background subtraction below.

Having characterized the ϕ signal, the pK^+K^- mass is plotted both for $m_{K^+K^-}$ in the ϕ signal region and for $m_{K^+K^-}$ in the ϕ sideband regions. Figure 3 shows the results. Each spectrum is fitted to a Gaussian for the signal with width fixed to $\sigma = 4.9$ MeV/c^2 from Monte Carlo, and a 2nd order Chebychev polynomial for the smooth background. The fit to the pK^+K^- mass spectrum corresponding to the ϕ signal region yields 54 ± 12 events with a confidence level of 97%. The mean mass for the signal is measured to be 2288.2 ± 1.3 MeV/c^2. In fitting the pK^+K^- mass corresponding to the ϕ sideband region, the mean Λ_c^+ mass is fixed to that obtained from the ϕ signal region and the σ is fixed to the Monte Carlo value as before. This gives -16.4 ± 9.6 events for the ϕ-sideband Λ_c^+ yield. Since the true contribution must be positive-definite, we set the central value to zero and use 0 ± 9.6 as the best estimate of the $\Lambda_c^+ \rightarrow pK^+K^-$ contribution. After scaling this by R_ϕ and subtracting, we find that the net $\Lambda_c^+ \rightarrow p\phi$ yield is 54 ± 13 events.

As a check of the non-resonant contribution to the $\Lambda_c^+ \rightarrow p\phi$ signal, we fit the K^+K^- mass spectra corresponding to the Λ_c^+ signal and sideband regions as determined from the inclusive pK^+K^- mass spectrum. The ϕ yield obtained from the Λ_c^+ sideband regions, $2.246 < m_{pKK} < 2.266$ and $2.306 < m_{pKK} < 2.326$ GeV/c^2, is subtracted from that for the Λ_c^+ signal region, $2.276 < m_{pKK} < 2.296$ GeV/c^2. Figure 4 shows the fits to the K^+K^- spectra from the Λ_c^+ signal and sideband regions, which yield ϕ signals of 92.2 ± 17.0 events and 36.5 ± 13.5 events, respectively. The Λ_c^+ sideband K^+K^- mass spectrum in the Figure 4 has been scaled by the Λ_c^+ signal-to-sideband scale factor of $R_{\Lambda_c^+} = 0.502 \pm 0.013$, obtained by integrating the background function in Figure 2 over the Λ_c^+ signal and sideband regions. This gives 56 ± 22 events for the $\Lambda_c^+ \rightarrow p\phi$ signal, which is in agreement with the first method.

A check is also made for a possible reflection from $D_s^+ \rightarrow \phi\pi^+$, where the pion is misidentified as a proton. It is found that the reflection is a broad enhancement in the mass region above the signal. The effect of this background is minimized by the tight particle-ID requirement on the proton. Consequently, the overall fake rate is less than 1%, causing negligible effect on the $\Lambda_c^+ \rightarrow p\phi$ signal yield from the fit.

The decay $\Lambda_c^+ \rightarrow pK^-\pi^+$ is used as the normalization mode for the $\Lambda_c^+ \rightarrow p\phi$ relative branching ratio. In finding the $\Lambda_c^+ \rightarrow pK^-\pi^+$ yield, the same cuts are applied as in the $\Lambda_c^+ \rightarrow pK^+K^-$ analysis to minimize systematic errors, except that the particle-ID for the π^+ is loosened to a consistency requirement: $\mathcal{P}_\pi > 0.001$. The $\Lambda_c^+ \rightarrow pK^-\pi^+$ mass spectrum is shown in Figure 5. The parameterization of the fit is the same as the $\Lambda_c^+ \rightarrow p\phi$ mass fit in Figure 3, except that the width of the Gaussian is allowed to vary. The fit yields 5683 ± 138 observed signal events with a mean of 2286.8 ± 0.2 MeV/c^2 and a width of 6.4 ± 0.2 MeV/c^2. If the width of the Gaussian is fixed to the Monte Carlo prediction of 5.8 MeV/c^2, the yield changes by 4%. This dependence is included in the systematic error.

Monte Carlo simulation is used to determine all aspects of the detection efficiency except particle-ID. The particle-ID efficiency for protons is obtained using a sample of 33000

$\Lambda \to p\pi^-$ decays with a signal-to-background ratio of 50:1 [14]. For protons thus identified, the momentum spectrum after the particle-ID cuts ($L_p > 0.9$, $\mathcal{P}_p > 0.001$) is divided by the momentum spectrum before these cuts, bin by bin, yielding the particle-ID efficiencies versus momentum. To calculate the detection efficiency, the measured efficiency is folded in by randomly rejecting the corresponding fraction of Monte Carlo tracks in each momentum bin. The particle-ID ($L_K > 0.1$, $\mathcal{P}_K > 0.001$) efficiency for the kaons is derived in an analogous manner, except that the kaons are taken from D^* decays through the cascade process $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$. A sample of 11000 such $D^0 \to K^-\pi^+$ decays is obtained with an 8:1 signal-to-background ratio [14]. The particle-ID efficiency for protons is near 90% from 300 MeV/c^2 to 1.1 GeV/c^2 falling off to below 10% by 2.5 GeV/c^2. For kaons the particle-ID efficiency remains relatively flat at about 95%.

Using a Monte Carlo sample of $\Lambda_c^+ \to p\phi$ decays, where the Λ_c^+ fragmentation takes place according to the Lund JETSET Monte Carlo [15], the full detection efficiency is determined, with the particle-ID portion folded in as described above. For $\Lambda_c^+ \to p\phi$, the overall efficiency is 0.178 ± 0.004 including the particle-ID efficiency which is 0.425 ± 0.011. For $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to pK^-\pi^+$ the overall efficiencies are 0.216 ± 0.005 and 0.224 ± 0.005, respectively.

Since for all the decay modes the requirement $x_p > 0.5$ is applied, the relative branching ratio for each mode is found simply by dividing the corrected yields. Table 1 gives the details, listing only the statistical errors. The $\phi \to K^+K^-$ branching ratio is explicitly included in the calculation of the $\Lambda_c^+ \to p\phi$ branching ratio, and its uncertainty is included in the systematic errors.

The estimates for the main sources of systematic error include the $\Lambda_c^+ \to p\phi$ and $\Lambda_c^+ \to pK^+K^-$ signal shapes (7% and 11%, respectively) and background shapes (2% and 10%, respectively), particle-ID efficiency (6%), and the $\Lambda_c^+ \to pK^-\pi^+$ fit (4%). In addition, for the $\Lambda_c^+ \to p\phi$ mode, varying the ϕ signal and sideband regions gives a 5% variation in the yield. Finally, there is a 1.8% contribution to the $\Lambda_c^+ \to p\phi$ systematic error from the $\phi \to K^+K^-$ branching ratio uncertainty. Thus we estimate 12% systematic error in $\mathcal{B}(p\phi)/\mathcal{B}(pK\pi)$, 17% in $\mathcal{B}(pKK)/\mathcal{B}(pK\pi)$, and 18% in $\mathcal{B}(p\phi)/\mathcal{B}(pKK)$. The final results appear in Table 2, along with those from NA32 [9] and E687 [10]. Also shown in the table are theoretical predictions from Cheng and Tseng [5], Körner and Krämer [6], Żenczykowski [7], and Datta [8].

In summary, we have observed the Cabibbo-suppressed decays $\Lambda_c^+ \to p\phi$ and $\Lambda_c^+ \to pK^+K^-$. The results appear in Table 2, which show that the phenomenological treatments of the $\Lambda_c^+ \to p\phi$ decay rate agree within a factor of two or three with our result. Our measure branching ratio $\mathcal{B}(p\phi)/\mathcal{B}(pKK)$ is consistent with the E687 upper limit, while our measurement of $\mathcal{B}(pKK)/\mathcal{B}(pK\pi)$ differs from the E687 result by 1.7 sigma. Within the factorization approach using a $1/N_c$ expansion, our result supports the validity of taking the large N_c limit in charm baryon decays.

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Table 1: Calculation of the branching ratios for $\Lambda_c^+ \to p\phi$ and $\Lambda_c^+ \to pK^+K^-$ relative to $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to pK^+K^-$. The errors are statistical only.

Λ_c^+ Decay Mode:	$\Lambda_c^+ \to p\phi$	$\Lambda_c^+ \to pK^+K^-$	$\Lambda_c^+ \to pK^-\pi^+$
Raw Yield	54 ± 12	214 ± 50	5683 ± 138
Efficiency	0.178 ± 0.004	0.216 ± 0.005	0.224 ± 0.005
$B(\phi \to K^+K^-)$	0.491 ± 0.005		
Corrected Yield	618 ± 138	991 ± 233	25371 ± 837
$B/B(\Lambda_c^+ \to pK^-\pi^+)$	0.024 ± 0.006	0.039 ± 0.009	1
$B/B(\Lambda_c^+ \to pK^+K^-)$	0.62 ± 0.20	1	

Table 2: Final results on $\Lambda_c^+ \to p\phi$ and $\Lambda_c^+ \to pK^+K^-$.

Ratio of interest:	$\mathcal{B}(p\phi)/\mathcal{B}(pK\pi)$	$\mathcal{B}(pKK)/\mathcal{B}(pK\pi)$	$\mathcal{B}(p\phi)/\mathcal{B}(pKK)$
This experiment	$0.024 \pm 0.006 \pm 0.003$	$0.039 \pm 0.009 \pm 0.007$	$0.62 \pm 0.20 \pm 0.12$
NA32	0.04 ± 0.03		
E687		$0.096 \pm 0.029 \pm 0.010$	$< 0.58@90\%C.L.$
Cheng & Tseng	0.045 ± 0.011		
Żenczykowski	0.023		
Datta	0.01		
Körner& Krämer	0.05		

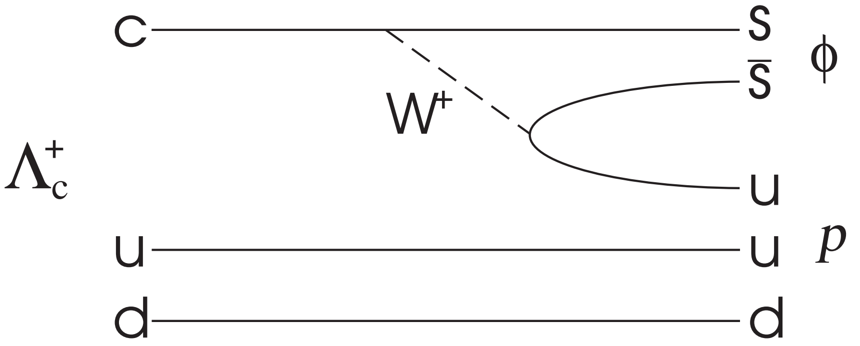

Figure 1: The decay $\Lambda_c^+ \to p\phi$.

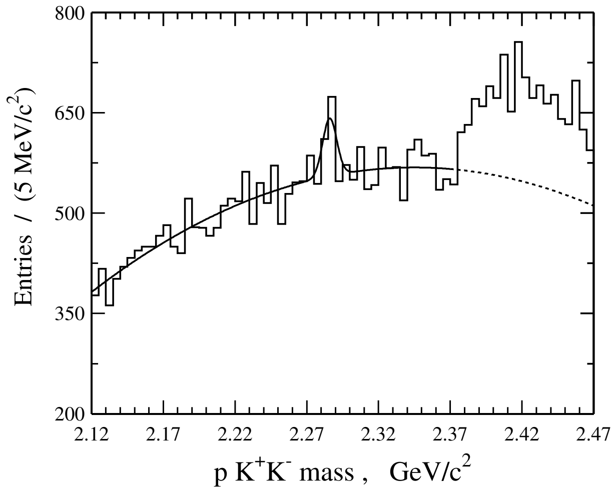

Figure 2: Invariant mass of inclusive pK^+K^- combinations passing all requirements. No ϕ cut is applied. The region above 2.37 GeV/c^2, where there is a large enhancement from $\Lambda_c^+ \to pK^-\pi^+$ decays, is not included in the fit.

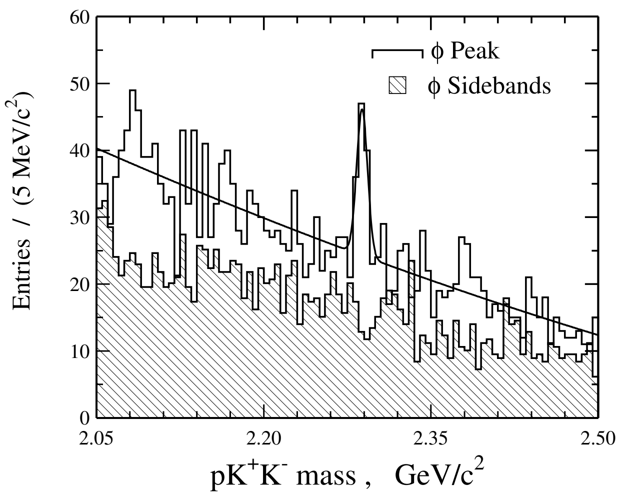

Figure 3: Invariant mass of pK^+K^- combinations corresponding to K^+K^- mass in the ϕ "signal" (unshaded) and "sideband" (shaded) regions.

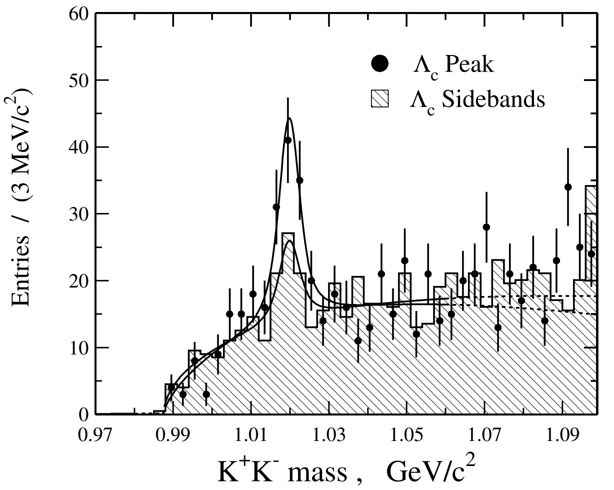

Figure 4: Fit to K^+K^- mass from combinations belonging to the Λ_c^+ signal (unshaded) and sideband (shaded) regions. The region above 1.06 GeV/c^2 is not included in the fit because of K^{*0} feed-up when the π is misidentified as a K.

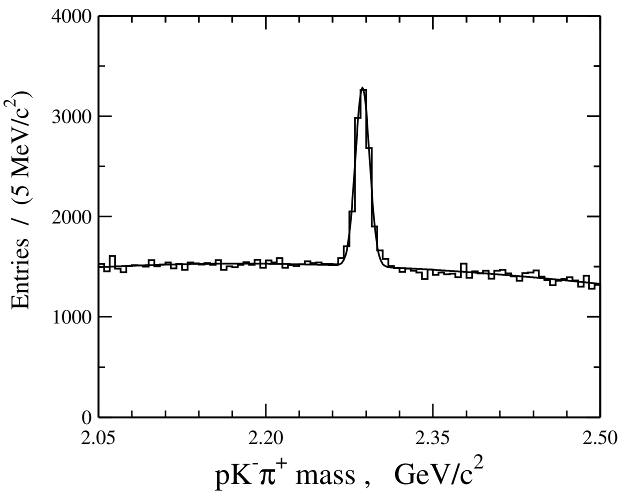

Figure 5: Invariant mass of $pK^-\pi^+$ combinations found in the same data sample. The $\Lambda_c^+ \to pK^-\pi^+$ signal is used for normalization of the $\Lambda_c^+ \to p\phi$ branching ratio.