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

Abstract

We report the observation of the Cabibbo-suppressed decays

$\Lambda_c^+ \rightarrow pK^+K^-$ and $\Lambda_c^+ \rightarrow p\phi$

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 $\Lambda_c^+ \rightarrow pK^-\pi^+$ 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, $B(D_s^+ \rightarrow K^{*0}K^+) / B(D_s^+ \rightarrow \phi\pi^+) \approx 1$ [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 $\Lambda_c^+ \rightarrow p\phi$, shown in Figure 1, is also naively expected to be color-suppressed. However, using factorization and taking the limit $N_c \rightarrow \infty$ leads to a prediction of no color-suppression [5]. The $\Lambda_c^+ \rightarrow p\phi$ decay receives contributions only from factorizable diagrams, and therefore a reliable calculation should be obtained using factorization. Observation of the decay mode $\Lambda_c^+ \rightarrow p\phi$ was first reported by the ACCMOR collaboration with $2.8 \pm 1.9$ events [9]. Last year the E687 collaboration published results on the first observation of the Cabibbo-suppressed charmed baryon decay $\Lambda_c^+ \rightarrow pK^+K^-$, along with an upper limit on the resonant...
substructure $\Lambda_c^+ \rightarrow p\phi$ [10]. Herein we present new CLEO results on the observation of $\Lambda_c^+ \rightarrow pK^+K^-$ and $\Lambda_c^+ \rightarrow p\phi$ 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 $\Lambda_c^+$ 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 $\chi^2$ probability $P_i$ for each mass hypothesis $i = \pi, K, p$. Using these probabilities $P_i$, a normalized probability ratio $L_i$ is evaluated for each track according to the formula: $L_i \equiv P_i/(P_\pi + P_K + P_p)$. 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 $P_p > 0.001$ and $P_K > 0.001$, respectively.

In order to reduce the large combinatoric background, the candidate $\Lambda_c^+$ 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 $\Lambda_c^+ \rightarrow pK^-\pi^+$, 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 2nd order Chebychev polynomial for the smooth background. This fit yields $214 \pm 50$ events for the inclusive $\Lambda_c^+ \rightarrow pK^+K^-$ signal with a mean mass of $2285.5 \pm 1.2$ MeV/c$^2$ [13].
To find a $\Lambda^+_c \rightarrow p\phi$ signal, we reconstruct $\phi$ candidates through their decays $\phi \rightarrow K^+K^-$. Because the width of the $\phi$ is comparable to the detector mass resolution, the $\phi$ 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 $\phi$ “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 $\phi$ background subtraction below.

In order to obtain the $\Lambda^+_c \rightarrow p\phi$ signal, the $pK^+K^-$ mass plot is made both for $m_{K^+K^-}$ in the $\phi$ signal region and the $\phi$ sideband regions. Figure 3 shows the results. The spectra are 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 $\phi$ signal region yields $54 \pm 12$ events with a confidence level of 97%. The mean mass for the signal is measured to be $2288.2 \pm 1.3$ MeV/$c^2$. In fitting the $pK^+K^-$ mass corresponding to the $\phi$ sideband region, the mean $\Lambda^+_c$ mass is fixed to that obtained from the $\phi$ signal region and the $\sigma$ is fixed to the Monte Carlo value as before. This gives $-16.4 \pm 9.6$ events for the $\phi$-sideband $\Lambda^+_c$ yield. Since the true contribution must be positive-definite, we set the central value to zero and use $0 \pm 9.6$ as the best estimate of the $\Lambda^+_c \rightarrow pK^+K^-$ contribution. After scaling this by $R_\phi$ and subtracting, we find that the net $\Lambda^+_c \rightarrow p\phi$ yield is $54 \pm 13$ events. This gives $-16.4 \pm 9.6$ events for the $\phi$-sideband $\Lambda^+_c$ yield. Since the true contribution must be positive-definite, we set the central value to zero and use $0 \pm 9.6$ as the best estimate of the $\Lambda^+_c \rightarrow pK^+K^-$ contribution. After scaling this by $R_\phi$ and subtracting, we find that the net $\Lambda^+_c \rightarrow p\phi$ yield is $54 \pm 13$ events. [ NOTE TO CLEO READERS: Please See the CLEO Appendix at the end of this document.]

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 $\Lambda^+_c$ signal and sideband regions as determined from the
inclusive \(pK^+K^-\) mass spectrum. The \(\phi\) yield obtained from the \(\Lambda_c^+\) sideband regions, \(2.246 < m_{pKK} < 2.266\) and \(2.306 < m_{pKK} < 2.326\) GeV/\(c^2\), is subtracted from that for the \(\Lambda_c^+\) signal region, \(2.276 < m_{pKK} < 2.296\) GeV/\(c^2\). Figure 4 shows the fits to the \(K^+K^-\) spectra from the \(\Lambda_c^+\) signal and sideband regions, which yield \(\phi\) signals of \(92.2 \pm 17.0\) events and \(36.5 \pm 13.5\) events, respectively. The \(\Lambda_c^+\) sideband \(K^+K^-\) mass spectrum in the Figure 4 has been scaled by the \(\Lambda_c^+\) 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 \(\Lambda_c^+\) signal and sideband regions. This gives \(56 \pm 22\) 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 \(\pi^+\) is loosened to a consistency requirement: \(P_{\pi} > 0.001\). 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 \(5683 \pm 138\) observed signal events with a mean of \(2286.8 \pm 0.2\) MeV/\(c^2\) and a width of \(6.4 \pm 0.2\) 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 \(33000\) \(\Lambda \rightarrow p\pi^-\) decays with a signal-to-background ratio of \(50:1\) [16]. For protons thus identified, the momentum spectrum after the particle-ID cuts (\(I_p > 0.9\), \(P_p > 0.001\)) 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 ($L_K > 0.1$, $P_K > 0.001$) efficiency for the kaons is derived in an analogous manner, except that the kaons are taken from $D^*$ decays through the cascade process $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$. A sample of 11000 such $D^0 \rightarrow K^- \pi^+$ decays is obtained with an 8:1 signal-to-background ratio [16]. 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 $\Lambda_c^+ \rightarrow p\phi$ decays, where the $\Lambda_c^+$ fragmentation takes place according to the Lund JETSET Monte Carlo [17], the full detection efficiency is determined, with the particle-ID portion folded in as described above. For $\Lambda_c^+ \rightarrow p\phi$, the overall efficiency is 0.178 ± 0.004 including the particle-ID efficiency which is 0.425 ± 0.011. For $\Lambda_c^+ \rightarrow pK^+K^-$ (non-resonant) and $\Lambda_c^+ \rightarrow pK^-\pi^+$ 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 I gives the details, listing only the statistical errors. The $\phi \rightarrow K^+K^-$ branching ratio is explicitly included in the calculation of the $\Lambda_c^+ \rightarrow p\phi$ branching ratio, and its uncertainty is included in the systematic errors.

The estimates for the main sources of systematic error include the $\Lambda_c^+ \rightarrow p\phi$ and $\Lambda_c^+ \rightarrow pK^+K^-$ signal shapes (7% and 11%, respectively) and background shapes (2% and 10%, respectively), particle-ID efficiency (6%), and the $\Lambda_c^+ \rightarrow pK^-\pi^+$ fit (4%). In addition, for the $\Lambda_c^+ \rightarrow p\phi$ mode, varying the $\phi$ signal and sideband regions gives a 5% variation in the yield. Finally, there is a 1.8% contribution to the $\Lambda_c^+ \rightarrow p\phi$ systematic error from the $\phi \rightarrow K^+K^-$ branching ratio uncertainty. Thus we estimate 12% systematic error in $B(p\phi/pK\pi)$, 17% in $B(pK^+pK^-\pi)$, and 18% in $B(p\phi/pKK')$. The final results appear in Table II, 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], Ženczykowski [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 II, 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. Since naive color suppression arguments would have required a \( \Lambda_c^+ \to p\phi \) decay rate much smaller (by a factor of about 15), our result suggests, at least for the factorizable diagrams, that color-suppression is inoperative in charm baryon decays [5]. Furthermore, 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.

[1] Particle Data Group, I. Monatet et al. Phys. Rev. D 50, 1173 (1994).

[2] Unless otherwise specified, reference to a state also implies reference to the charge conjugate state.

[3] A. J. Buras, J.-M. Gérard, and R. Rückl, Nuc. Phys. B268, 16 (1986).

[4] M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C 34, 103 (1987).

[5] H. Cheng and B. Tseng, Phys. Rev. D 46, 1042 (1992).

[6] J.G. Körner and M. Krämer, Z. Phys. C 55, 659 (1992).

[7] P. Żenczykowski, Phys. Rev. D 50, 402 (1994).

[8] A. Datta, UH-511-824-95, April 1995.

[9] S. Barlag et al., Z. Phys. C 48, 29 (1990).

[10] P.L. Frabetti et al., Phys. Lett. B 314, 477–481 (1993).

[11] Y. Kubota et al., Nucl. Instrum. Methods A320, 66–113 (1992).

[12] The Monte Carlo employs the CERN GEANT package:
R. Brun et al., GEANT 3.14, CERN DD/EE/84-1.

[13] The quoted uncertainties in mass measurements refer to statistical error only.

[14] The remaining background is removed by sideband subtraction.

[15] T. Sjöstrand, Comp. Phys. Comm., 43 367 (1987).
FIG. 1. The decay $\Lambda_c^+ \rightarrow p\phi$.

FIG. 2. Invariant mass of inclusive $pK^+K^-$ combinations passing all requirements. No $\phi$ cut is applied. The region above 2.37 GeV/c$^2$, where there is a large enhancement from $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays, is not included in the fit.
FIG. 3. Invariant mass of $pK^+K^-$ combinations corresponding to $K^+K^-$ mass in the $\phi$ “signal” (unshaded) and “sideband” (shaded) regions.

FIG. 4. Fit to $K^+K^-$ mass from combinations belonging to the $\Lambda_c^+$ 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 $\pi$ is misidentified as a $K$. 
FIG. 5. Invariant mass of $pK^−π^+$ combinations found in the same data sample. The $Λ_c^+ → pK^−π^+$ signal is used for normalization of the $Λ_c^+ → p\phi$ branching ratio.
TABLE I. Calculation of the branching ratios for $\Lambda_c^+ \rightarrow p\phi$ and $\Lambda_c^+ \rightarrow pK^+K^-$ relative to $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^+K^-$. The errors are statistical only.

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

TABLE II. Final results on $\Lambda_c^+ \rightarrow p\phi$ and $\Lambda_c^+ \rightarrow pK^+K^-$. 

| 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 ± 0.006 ± 0.003                     | 0.039 ± 0.009 ± 0.007                   | 0.62 ± 0.20 ± 0.12                    |
| NA32                                       | 0.04 ± 0.03                               |                                        |                                        |
| E687                                       |                                            | 0.096 ± 0.029 ± 0.010                  | < 0.58@90%C.L.                         |
| Cheng & Tseng                              | 0.045 ± 0.011                             |                                        |                                        |
| Żenczykowski                               | 0.023                                     |                                        |                                        |
| Datta                                      | 0.01                                      |                                        |                                        |
| Körner & Krämer                            | 0.05                                      |                                        |                                        |