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Observation of the Cabibbo-suppressed charmed baryon decay $\Lambda_c^+ \to p\phi$

J. P. Alexander,[1] C. Bebek,[1] B. E. Berger,[1] K. Berkelman,[1] K. Bloom,[1] T. E. Browder,[1,*] D. G. Cassel,[1] H. A. Cho,[1] D. M. Coffman,[1] D. S. Crowcroft,[1] M. Dickson,[1] P. S. Drell,[1] D. J. Dumas,[1] R. Ehrlich,[1] R. Elia,[1] P. Gaidarev,[1] M. Garcia-Sciveres,[1] B. Gittelman,[1] S. W. Gray,[1] D. L. Hartill,[1] B. K. Heltsley,[1] S. Henderson,[1] C. D. Jones,[1] S. L. Jones,[1] J. Kandaswamy,[1] N. Katayama,[1] P. C. Kim,[1] D. L. Kreinick,[1] T. Lee,[1] Y. Liu,[1] G. S. Ludwig,[1] J. Masui,[1] J. Mevissen,[1] N. B. Mistry,[1] C. R. Ng,[1] E. Nordberg,[1] J. R. Patterson,[1] D. Peterson,[1] D. Riley,[1] A. Soffer,[1] P. Avery,[2] A. Freyberger,[2] K. Lingel,[2] C. Prescott,[2] J. Rodriguez,[2] S. Yang,[2] J. Yelton,[2] G. Brandenburg,[3] D. Cinabro,[3] T. Liu,[3] M. Saulnier,[3] R. Wilson,[3] H. Yamamoto,[3] T. Bergfeld,[4] B. I. Eisenstein,[4] J. Ernst,[4] G. E. Gladding,[4] G. D. Gollin,[4] M. Palmer,[4] M. Selen,[4] J. J. Thaler,[4] K. W. Edwards,[5] K. W. McLean,[5] M. Ogg,[5] A. Bellerive,[6] D. I. Britton,[6] E. R. F. Hyatt,[6] R. Janicek,[6] D. B. MacFarlane,[6] P. M. Patel,[6] B. Spaan,[6] A. J. Sadoff,[7] R. Ammar,[8] P. Baringer,[8] A. Bean,[8] D. Besson,[8] D. Coppage,[8] N. Copty,[8] R. Davis,[8] N. Hancock,[8] S. Kotov,[8] I. Kravchenko,[8] N. Kwak,[8] Y. Kubota,[9] M. Lattery,[9] M. Momayezi,[9] J. K. Nelson,[9] S. Patton,[9] R. Poling,[9] V. Savinov,[9] S. Schrenk,[9] R. Wang,[9] M. S. Alam,[10] I. J. Kim,[10] Z. Ling,[10] A. H. Mahmood,[10] J. J. O'Neill,[10] H. Severini,[10] C. R. Sun,[10] F. Wappler,[10] G. Crawford,[11] R. Fulton,[11] D. Fujino,[11] K. K. Gan,[11] K. Honscheid,[11] H. Kagan,[11] R. Kass,[11] J. Lee,[11] M. Sung,[11] C. White,[11] A. Wolf,[11] M. M. Zoeller,[11] X. Fu,[12] B. Nemati,[12] W. R. Ross,[12] P. Skubic,[12] M. Wood,[12] M. Bishai,[13] J. Fast,[13] E. Gerndt,[13] J. W. Hinson,[13] T. Miao,[13] D. H. Miller,[13] M. Modesitt,[13] E. I. Shibata,[13] I. P. J. Shipsey,[13] P. N. Wang,[13] L. Gibbons,[14] S. D. Johnson,[14] Y. Kwon,[14] S. Roberts,[14] E. H. Thorndike,[14] T. E. Coan,[15] J. Dominick,[15] V. Fadeyev,[15] I. Korolkov,[15] M. Lambrecht,[15] S. Sanghera,[15] V. Shelkov,[15] T. Skwarnicki,[15] R. Stroynowski,[15] I. Volobouev,[15] G. Wei,[15] M. Artuso,[16] M. Gao,[16] M. Goldberg,[16] D. He,[16] N. Horwitz,[16] S. Kopp,[16] G. C. Moneti,[16] R. Mountain,[16] F. Muheim,[16] Y. Mukhin,[16] S. Playfer,[16] S. Stone,[16] X. Xing,[16] J. Bartelt,[17] S. E. Csorna,[17] V. Jain,[17] S. Marka,[17] D. Gibaut,[18] K. Kinoshita,[18] P. Pomianowski,[18] B. Barish,[19] M. Chadha,[19] S. Chan,[19] D. F. Cowen,[19] G. Eigen,[19] J. S. Miller,[19] C. O'Grady,[19] J. Urheim,[19] A. J. Weinstein,[19] F. Würthwein,[19] D. M. Asner,[20] M. Athanas,[20] D. W. Bliss,[20] W. S. Brower,[20] G. Masek,[20] H. P. Paar,[20] J. Gronberg,[21] C. M. Korte,[21] R. Kutschke,[21] S. Menary,[21] R. J. Morrison,[21] S. Nakanishi,[21] H. N. Nelson,[21] T. K. Nelson,[21] C. Qiao,[21] J. D. Richman,[21] D. Roberts,[21] A. Ryd,[21] H. Tajima,[21] M. S. Witherell,[21] R. Balest,[22] K. Cho,[22] W. T. Ford,[22] M. Lohner,[22] H. Park,[22] P. Rankin,[22] and J. G. Smith[22]

[1]*Cornell University, Ithaca, New York 14853*

[2]*University of Florida, Gainesville, Florida 32611*

[3]*Harvard University, Cambridge, Massachusetts 02138*

[4]*University of Illinois, Champaign-Urbana, Illinois, 61801*

[5]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
and the Institute of Particle Physics, University of Ottawa Campus, Ottawa, Ontario, Canada K1N 9B4

[6]*McGill University, Montréal, Québec, Canada H3A 2T8*
and the Institute of Particle Physics, University of Ottawa Campus, Ottawa, Ontario, Canada K1N 9B4

[7]*Ithaca College, Ithaca, New York 14850*

[8]*University of Kansas, Lawrence, Kansas 66045*

[9]*University of Minnesota, Minneapolis, Minnesota 55455*

[*]Permanent address: University of Hawaii at Manoa.

[10]State University of New York at Albany, Albany, New York 12222
[11]Ohio State University, Columbus, Ohio, 43210
[12]University of Oklahoma, Norman, Oklahoma 73019
[13]Purdue University, West Lafayette, Indiana 47907
[14]University of Rochester, Rochester, New York 14627
[15]Southern Methodist University, Dallas, Texas 75275
[16]Syracuse University, Syracuse, New York 13244
[17]Vanderbilt University, Nashville, Tennessee 37235
[18]Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061
[19]California Institute of Technology, Pasadena, California 91125
[20]University of California, San Diego, La Jolla, California 92093
[21]University of California, Santa Barbara, California 93106
[22]University of Colorado, Boulder, Colorado 80309-0390

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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.

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The strength of color suppression in internal W-emission charmed meson decays has long been in question. For example, $\mathscr{B}(D_s^+ \to \bar{K}^{*0}K^+)/\mathscr{B}(D_s^+ \to \phi\pi^+) \simeq 1$, [1,2] while the expectation from color-matching requirements is that this ratio should be about 1/9. 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 Fig. 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 identification (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 $\mathscr{P}_i$ for each mass hypothesis $i=\pi,K,p$. Using these probabilities $\mathscr{P}_i$, a normalized probability ratio L_i is evaluated for each track according to the formula $L_i \equiv \mathscr{P}_i/(\mathscr{P}_\pi + \mathscr{P}_K + \mathscr{P}_p)$. 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 $\mathscr{P}_p>0.001$ and $\mathscr{P}_K>0.001$, respectively. In order to reduce the large combinatoric background, the candidate Λ_c^+ scaled momentum $x_p = P_{\Lambda c}/\sqrt{E_{\rm beam}^2 - m_{\Lambda c}^2}$ is limited to $x_p>0.5$.

The pK^-K^+ invariant mass is shown in Fig. 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 second-order Chebyshev 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].

The ϕ candidates are reconstructed 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 function of width $\Gamma=4.43$ MeV/c^2 [1]. The background is parametrized by a function of the form $b(m)$

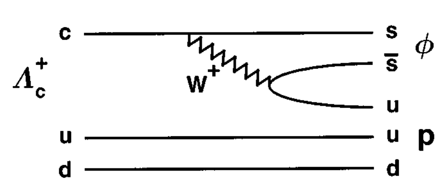

FIG. 1. The decay $\Lambda_c^+ \to p\phi$.

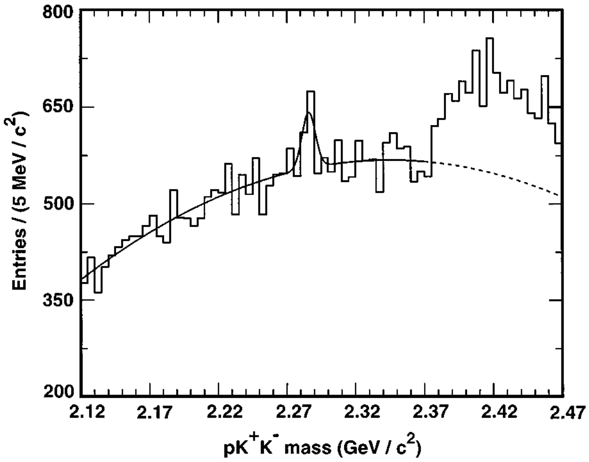

FIG. 2. Invariant mass of inclusive pK^-K^+ combinations passing all requirements. No ϕ cut is applied. The region above 2.37 GeV/c^2, where there is a large enhancement from $\Lambda_c^+ \to pK^-\pi^+$ decays, is not included in the fit.

$=N(m-m_0)^{\alpha}e^{\beta(m-m_0)}$. The measured Gaussian resolution from the fit is $\sigma=1.6\pm0.2$ 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 $R_{\phi}=0.560\pm0.016$, which is used in the ϕ background subtraction below.

In order to obtain the $\Lambda_c^+ \to p\phi$ signal, the pK^-K^+ mass plot is made both for $m_{K^-K^+}$ in the ϕ signal region and the ϕ 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 simulation, and a second-order Chebyshev 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

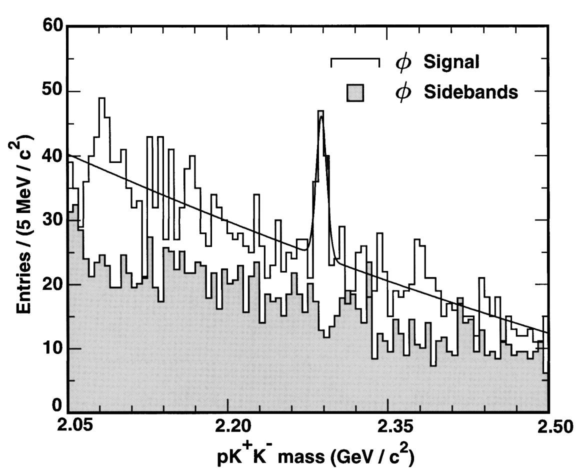

FIG. 3. Invariant mass of pK^-K^+ combinations corresponding to K^-K^+ mass in the ϕ signal and sideband regions.

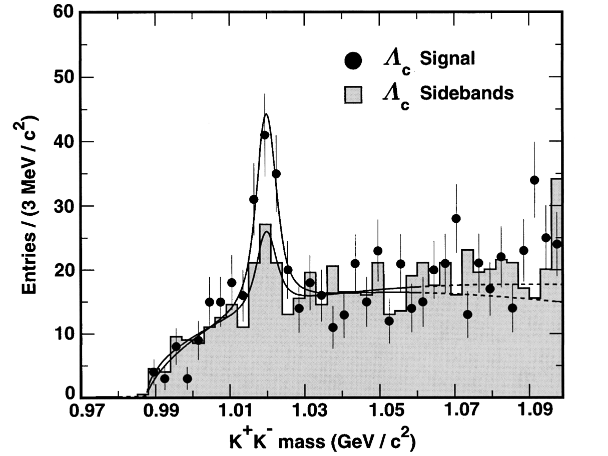

FIG. 4. Fit to K^-K^+ mass from combinations belonging to the Λ_c^+ signal and sideband regions. The region above 1.06 GeV/c^2 is not included in the fit because of K^{*0} feed-up when the π is misidentified as a K.

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 $\Lambda_c^+ \to pK^-K^+$ contribution. After scaling this by R_{ϕ} and subtracting we find that the net $\Lambda_c^+ \to p\phi$ yield is 54 ± 13 events.

As a check of the nonresonant contribution to the $\Lambda_c^+ \to p\phi$ 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 Fig. 4 has been scaled by the Λ_c^+ signal-to-sideband scale factor of $R_{\Lambda_c^+}=0.502\pm0.013$, obtained by integrating the background function in Fig. 2 over

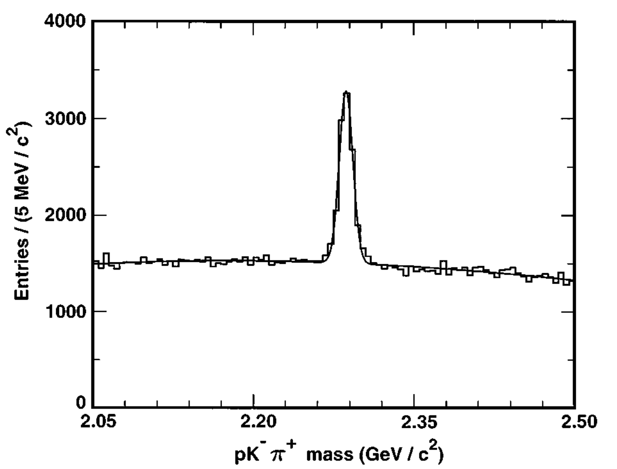

FIG. 5. Invariant mass of $pK^-\pi^+$ combinations found in the same data sample. The $\Lambda_c^+ \to pK^-\pi^+$ signal is used for normalization of the $\Lambda_c^+ \to p\phi$ branching ratio.

TABLE I. 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.

Decay mode:	$\Lambda_c^+ \to p\phi$	$\Lambda_c^+ \to pK^-K^+$	$\Lambda_c^+ \to pK^-\pi^+$
Raw yield	54 ± 13	214 ± 50	5683 ± 138
Efficiency	0.178 ± 0.004	0.216 ± 0.005	0.224 ± 0.005
$\mathcal{B}(\phi \to K^-K^+)$	0.491 ± 0.005		
Corr. yield	618 ± 138	991 ± 233	25371 ± 837
$\mathcal{B}/\mathcal{B}(pK^-\pi^+)$	0.024 ± 0.006	0.039 ± 0.009	1
$\mathcal{B}/\mathcal{B}(pK^-K^+)$	0.62 ± 0.20	1	

the Λ_c^+ signal and sideband regions. This gives 56 ± 22 events for the $\Lambda_c^+ \to p\phi$ signal, which is in agreement with the first method.

A check is also made for a possible reflection from $D_s^+ \to \phi\pi^+$, 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 reduction of the $\Lambda_c^+ \to p\phi$ signal yield from the fit.

The decay $\Lambda_c^+ \to pK^-\pi^+$ is used as the normalization mode for the $\Lambda_c^+ \to p\phi$ relative branching ratio. In finding the $\Lambda_c^+ \to pK^-\pi^+$ yield, the same cuts are applied as in the $\Lambda_c^+ \to pK^-K^+$ 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 $\Lambda_c^+ \to pK^-\pi^+$ mass spectrum is shown in Fig. 5. The parametrization of the fit is the same as the $\Lambda_c^+ \to p\phi$ mass fit in Fig. 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 33 000 $\Lambda \to p\pi^-$ 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. The measured particle-ID efficiency is incorporated into the Monte Carlo simulation by randomly rejecting the corresponding fraction of 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 11 000 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 to 1.1 GeV/c falling off to below 10% by 2.5 GeV/c. 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 simulation [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 I gives the details, listing only the statistical 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 II, along with those from NA32 [9] and E687 [10] and theoretical predictions from Cheng and Tseng [5], Körner and Krämer [6], Żenczykowski [7], and Datta [8]. From Table I we also find $\mathcal{B}(\Lambda_c^+ \to pK^-K^+[\text{non-}\phi]) = 0.029\pm0.010\pm0.005$ for $\Lambda_c^+ \to pK^-K^+$ decays not arising from $\Lambda_c^+ \to p\phi$.

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

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

Ratio of interest	$\mathcal{B}(p\phi)/\mathcal{B}(pK^-\pi^+)$	$\mathcal{B}(p\phi)/\mathcal{B}(pK^-K^+)$	$\mathcal{B}(pK^-K^+)/\mathcal{B}(pK^-\pi^+)$
This experiment	$0.024\pm0.006\pm0.003$	$0.62\pm0.20\pm0.12$	$0.039\pm0.009\pm0.007$
NA32 [9]	0.04 ± 0.03		
E687 [10]		<0.58 at 90% C.L.	$0.096\pm0.029\pm0.010$
Cheng and Tseng [5]	0.045 ± 0.011		
Żenczykowski	0.023		
Körner and Krämer [6]	0.05		
Datta [8]	0.01		

[a]Reference [7], using Ref. [1] for $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

of the $\Lambda_c^+ \to p\phi$ decay rate agree within a factor of 2 or 3 with our result. Our measured branching ratio $\mathscr{B}(p\phi)/\mathscr{B}(pKK)$ is consistent with the E687 upper limit, while our measurement of $\mathscr{B}(pKK)/\mathscr{B}(pK\pi)$ differs from the E687 result by 1.7 σ. 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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