

Improved Measurement of the Form Factors in the Decay $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$

J. W. Hinson,¹ G. S. Huang,¹ J. Lee,¹ D. H. Miller,¹ V. Pavlunin,¹ R. Rangarajan,¹ B. Sanghi,¹ E. I. Shibata,¹ I. P. J. Shipsey,¹ D. Cronin-Hennessy,² C. S. Park,² W. Park,² J. B. Thayer,² E. H. Thorndike,² T. E. Coan,³ Y. S. Gao,³ F. Liu,³ R. Stroynowski,³ M. Artuso,⁴ C. Boulahouache,⁴ S. Blusk,⁴ E. Dambasuren,⁴ O. Dorjkhaidav,⁴ R. Mountain,⁴ H. Muramatsu,⁴ R. Nandakumar,⁴ T. Skwarnicki,⁴ S. Stone,⁴ J. C. Wang,⁴ S. E. Csorna,⁵ I. Danko,⁵ G. Bonvicini,⁶ D. Cinabro,⁶ M. Dubrovin,⁶ S. McGee,⁶ A. Bornheim,⁷ E. Lipeles,⁷ S. P. Pappas,⁷ A. Shapiro,⁷ W. M. Sun,⁷ A. J. Weinstein,⁷ R. A. Briere,⁸ G. P. Chen,⁸ T. Ferguson,⁸ G. Tatishvili,⁸ H. Vogel,⁸ M. E. Watkins,⁸ N. E. Adam,⁹ J. P. Alexander,⁹ K. Berkelman,⁹ V. Boisvert,⁹ D. G. Cassel,⁹ J. E. Dubosq,⁹ K. M. Ecklund,⁹ R. Ehrlich,⁹ R. S. Galik,⁹ L. Gibbons,⁹ B. Gittelman,⁹ S. W. Gray,⁹ D. L. Hartill,⁹ B. K. Heltsley,⁹ L. Hsu,⁹ C. D. Jones,⁹ J. Kandaswamy,⁹ D. L. Kreinick,⁹ A. Magerkurth,⁹ H. Mahlke-Krüger,⁹ T. O. Meyer,⁹ N. B. Mistry,⁹ J. R. Patterson,⁹ D. Peterson,⁹ J. Pivarski,⁹ S. J. Richichi,⁹ D. Riley,⁹ A. J. Sadoff,⁹ H. Schwarthoff,⁹ M. R. Shepherd,⁹ J. G. Thayer,⁹ D. Urner,⁹ T. Wilksen,⁹ A. Warburton,⁹ M. Weinberger,⁹ S. B. Athar,¹⁰ P. Avery,¹⁰ L. Brevina-Newell,¹⁰ V. Potlia,¹⁰ H. Stoeck,¹⁰ J. Yelton,¹⁰ K. Benslama,¹¹ C. Cawfield,¹¹ B. I. Eisenstein,¹¹ G. D. Gollin,¹¹ I. Karliner,¹¹ N. Lowrey,¹¹ C. Plager,¹¹ C. Sedlack,¹¹ M. Selen,¹¹ J. J. Thaler,¹¹ J. Williams,¹¹ K. W. Edwards,¹² D. Besson,¹³ S. Anderson,¹⁴ V. V. Frolov,¹⁴ D. T. Gong,¹⁴ Y. Kubota,¹⁴ S. Z. Li,¹⁴ R. Poling,¹⁴ A. Smith,¹⁴ C. J. Stepaniak,¹⁴ J. Urheim,¹⁴ Z. Metreveli,¹⁵ K. K. Seth,¹⁵ A. Tomaradze,¹⁵ P. Zweber,¹⁵ S. Ahmed,¹⁶ M. S. Alam,¹⁶ J. Ernst,¹⁶ L. Jian,¹⁶ M. Saleem,¹⁶ F. Wappler,¹⁶ K. Arms,¹⁷ E. Eckhart,¹⁷ K. K. Gan,¹⁷ C. Gwon,¹⁷ K. Honscheid,¹⁷ H. Kagan,¹⁷ R. Kass,¹⁷ T. K. Pedlar,¹⁷ E. von Toerne,¹⁷ H. Severini,¹⁸ P. Skubic,¹⁸ S. A. Dytman,¹⁹ J. A. Mueller,¹⁹ S. Nam,¹⁹ and V. Savinov¹⁹

(CLEO Collaboration)

¹Purdue University, West Lafayette, Indiana 47907, USA

²University of Rochester, Rochester, New York 14627, USA

³Southern Methodist University, Dallas, Texas 75275, USA

⁴Syracuse University, Syracuse, New York 13244, USA

⁵Vanderbilt University, Nashville, Tennessee 37235, USA

⁶Wayne State University, Detroit, Michigan 48202, USA

⁷California Institute of Technology, Pasadena, California 91125, USA

⁸Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

⁹Cornell University, Ithaca, New York 14853, USA

¹⁰University of Florida, Gainesville, Florida 32611, USA

¹¹University of Illinois, Urbana-Champaign, Illinois 61801, USA

¹²Carleton University, Ottawa, Ontario, Canada K1S 5B6 and the Institute of Particle Physics, Canada

¹³University of Kansas, Lawrence, Kansas 66045, USA

¹⁴University of Minnesota, Minneapolis, Minnesota 55455, USA

¹⁵Northwestern University, Evanston, Illinois 60208, USA

¹⁶State University of New York at Albany, Albany, New York 12222, USA

¹⁷The Ohio State University, Columbus, Ohio 43210, USA

¹⁸University of Oklahoma, Norman, Oklahoma 73019, USA

¹⁹University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

(Received 29 December 2004; published 17 May 2005)

Using the CLEO detector at the Cornell Electron Storage Ring, we have studied the distribution of kinematic variables in the decay $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$. By performing a four-dimensional maximum likelihood fit, we determine the form factor ratio, $R = f_2/f_1 = -0.31 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$, the pole mass, $M_{\text{pole}} = [2.21 \pm 0.08(\text{stat}) \pm 0.14(\text{syst})] \text{ GeV}/c^2$, and the decay asymmetry parameter of the Λ_c^+ , $\alpha_{\Lambda_c} = -0.86 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$, for $\langle q^2 \rangle = 0.67 \text{ (GeV}/c^2)^2$. We compare the angular distributions of the Λ_c^+ and $\bar{\Lambda}_c^-$ and find no evidence for CP violation: $\mathcal{A}_{\Lambda_c} = \frac{(\alpha_{\Lambda_c^+} + \alpha_{\Lambda_c^-})}{(\alpha_{\Lambda_c^+} - \alpha_{\Lambda_c^-})} = 0.00 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02$, where the third error is from the uncertainty in the world average of the CP -violating parameter, \mathcal{A}_{Λ} , for $\Lambda \rightarrow p\pi^-$.

DOI: 10.1103/PhysRevLett.94.191801

PACS numbers: 13.30.Ce, 11.30.Er, 14.20.Lq, 14.65.Dw

The charm quark is unstable and decays via a first order weak interaction. In semileptonic decays, which are analogs of neutron β decay, the charm quark disintegrates

predominantly into a strange quark, a positron, and a neutrino. The rate depends on the weak quark mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix element

$|V_{cs}|$ and strong interaction effects, parametrized by form factors, which come into play because the charm quark is bound with light quarks to form a meson or baryon. Charm semileptonic decays allow a measurement of the form factors because $|V_{cs}|$ is tightly constrained by the unitarity of the CKM matrix [1].

Within the framework of heavy quark effective theory (HQET) [2], semileptonic ($J^P = 1/2^+ \rightarrow 1/2^+$) transitions of Λ -type baryons are simpler than mesons as they consist of a heavy quark and a spin and isospin zero light diquark. This simplicity leads to more reliable predictions [3,4] for form factors in heavy-to-light transitions. The measurement of form factors in the $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ transition provides a test of HQET predictions in the charm baryon sector, a test of lattice QCD, and information for the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ using Λ_b^0 decays since HQET relates the form factors in Λ_c^+ semileptonic decays to those governing Λ_b^0 semileptonic transitions.

In the limit of negligible lepton mass, the semileptonic ($J^P = 1/2^+ \rightarrow 1/2^+$) transition of a Λ -type baryon is

parametrized in terms of four form factors: two axial form factors, F_1^A and F_2^A , and two vector form factors, F_1^V and F_2^V . These form factors are functions of q^2 , the invariant mass squared of the virtual W^+ . The decay can be described in terms of helicity amplitudes $H_{\lambda_\Lambda \lambda_W}^V$ and $H_{\lambda_\Lambda \lambda_W}^A$, where λ_Λ and λ_W are the helicities of the Λ and W^+ . The helicity amplitudes are related to the form factors in the following way [4]:

$$\begin{aligned} \sqrt{q^2} H_{1/2 0}^V &= \sqrt{Q_-} [(M_{\Lambda_c} + M_\Lambda) F_1^V - q^2 F_2^V], \\ H_{1/2 1}^V &= \sqrt{2Q_-} [-F_1^V + (M_{\Lambda_c} + M_\Lambda) F_2^V], \\ \sqrt{q^2} H_{1/2 0}^A &= \sqrt{Q_+} [(M_{\Lambda_c} - M_\Lambda) F_1^A + q^2 F_2^A], \\ H_{1/2 1}^A &= \sqrt{2Q_+} [-F_1^A - (M_{\Lambda_c} - M_\Lambda) F_2^A], \end{aligned} \quad (1)$$

where $Q_\pm = (M_{\Lambda_c} \pm M_\Lambda)^2 - q^2$. The remaining helicity amplitudes can be obtained using the parity relations $H_{-\lambda_\Lambda -\lambda_W}^{V(A)} = +(-)H_{\lambda_\Lambda \lambda_W}^{V(A)}$. In terms of the helicity amplitudes, the decay angular distribution can be written as [4,5]

$$\begin{aligned} \Gamma_S &= \frac{d\Gamma}{dq^2 d\cos\theta_\Lambda d\cos\theta_W d\chi} \\ &= \mathcal{B}(\Lambda \rightarrow p\pi^-) \frac{1}{2} \frac{G_F^2}{(2\pi)^4} |V_{cs}|^2 \frac{q^2 P}{24M_{\Lambda_c}^2} \left\{ \frac{3}{8} (1 - \cos\theta_W)^2 |H_{1/2 1}|^2 (1 + \alpha_\Lambda \cos\theta_\Lambda) + \frac{3}{8} (1 + \cos\theta_W)^2 |H_{-1/2 -1}|^2 (1 - \alpha_\Lambda \cos\theta_\Lambda) \right. \\ &\quad + \frac{3}{4} \sin^2\theta_W [|H_{1/2 0}|^2 (1 + \alpha_\Lambda \cos\theta_\Lambda) + |H_{-1/2 0}|^2 (1 - \alpha_\Lambda \cos\theta_\Lambda)] \\ &\quad \left. - \frac{3}{2\sqrt{2}} \alpha_\Lambda \cos\chi \sin\theta_W \sin\theta_\Lambda [(1 - \cos\theta_W) \text{Re}(H_{-1/2 0} H_{1/2 1}^*) + (1 + \cos\theta_W) \text{Re}(H_{1/2 0} H_{-1/2 -1}^*)] \right\}, \end{aligned} \quad (2)$$

where G_F is the Fermi coupling constant, $|V_{cs}|$ is a CKM matrix element, P is the magnitude of the Λ momentum in the Λ_c^+ rest frame, $H_{\lambda_\Lambda \lambda_W} \equiv H_{\lambda_\Lambda \lambda_W}^V + H_{\lambda_\Lambda \lambda_W}^A$, θ_Λ is the angle between the momentum vector of the proton in the Λ rest frame and the Λ momentum in the Λ_c^+ rest frame, θ_W is the angle between the momentum vector of the positron in the W^+ rest frame and the Λ momentum in the Λ_c^+ rest frame, χ is the angle between the decay planes of the Λ and W^+ , and α_Λ is the $\Lambda \rightarrow p\pi^-$ decay asymmetry parameter measured to be 0.642 ± 0.013 [1].

In HQET, the heavy flavor and spin symmetries imply relations among the form factors and reduce their number to one when the decay involves only heavy quarks. For heavy-to-light transitions, two form factors are needed to describe the hadronic current. In this Letter, we follow Ref. [4], in which the c quark is treated as heavy and the s quark as light. Two independent form factors f_1 and f_2 are related to the standard form factors in the following way: $F_1^V(q^2) = -F_1^A(q^2) = f_1(q^2) + \frac{M_\Lambda}{M_{\Lambda_c}} f_2(q^2)$ and $F_2^V(q^2) = -F_2^A(q^2) = \frac{1}{M_{\Lambda_c}} f_2(q^2)$. In general, f_2 is expected to be negative and smaller in magnitude than f_1 . If the s quark is treated as heavy, f_2 is zero.

In order to extract the form factor ratio $R = f_2/f_1$ from a fit to the decay rate, Γ_S , an assumption must be made about the q^2 dependence of the form factors. The model of Körner and Krämer (KK) [4] uses the dipole form $f(q^2) = \frac{f(q_{\text{max}}^2)}{(1 - q^2/M_{\text{pole}}^2)^2} (1 - \frac{q_{\text{max}}^2}{M_{\text{pole}}^2})^2$ for both form factors, where the pole mass is taken from the naive pole dominance model: $M_{\text{pole}} = m_{D_s^*} = 2.11 \text{ GeV}/c^2$.

In this Letter, we perform, for the first time, a simultaneous fit for the form factor ratio and pole mass in the decay $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$, and we make a first search for CP violation in this decay. The data sample used in this study was collected with the CLEO II [6] and upgraded CLEO II.V [7] detectors operating at the Cornell Electron Storage Ring (CESR). The integrated luminosity consists of 13.7 fb^{-1} taken at and just below the $Y(4S)$ resonance, corresponding to approximately $18 \times 10^6 e^+ e^- \rightarrow c\bar{c}$ events. Throughout this Letter charge conjugate states are implicitly included, unless otherwise indicated, and the symbol e is used to denote an electron or positron.

The analysis is an extension of the technique described in [8,9]. The decay $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ is reconstructed by detecting a Λe^+ pair with invariant mass in the range

$m_{\Lambda_c^+} < m_{\Lambda_c}$. The positron is required to come from the region of the event vertex. To reduce the background from B decays, we require $R_2 = H_2/H_0 > 0.2$, where H_i are Fox-Wolfram event shape variables [10]. Positrons are identified using a likelihood function, which incorporates information from the calorimeter and dE/dx systems. The minimum allowed momentum for positron candidates is $0.7 \text{ GeV}/c$, as the positron fake rates are much higher at lower momentum. Positrons must be detected in the region: $|\cos\theta| < 0.7$, where θ is the angle between the positron momentum and the beam line. (Muons are not used as $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$ produces predominantly low momentum leptons for which the CLEO muon identification is not efficient.) The Λ is reconstructed in the decay mode $\Lambda \rightarrow p\pi^-$. The Λ baryon is long-lived ($c\tau = 7.89 \text{ cm}$); accordingly, the Λ vertex is required to be greater than 5 mm from the primary vertex in the $r - \phi$ plane, but the Λ momentum must extrapolate to the primary vertex. The dE/dx measurement of the proton is required to be consistent with the expected value. Combinations that satisfy interpretation as a K_S^0 are rejected. The magnitude of the Λ momentum is required to be greater than $0.8 \text{ GeV}/c$ in order to reduce combinatorial background. These Λ candidates are then combined with right sign (RS) tracks consistent with positrons, and the sum of the Λ and e^+ momenta is required to be greater than $1.4 \text{ GeV}/c$ in order to reduce the background from B decays.

The above selection criteria permit the isolation of signal events with low background. The number of events passing the selection is 4060, of which 123 ± 12 are consistent with fake Λ background, 338 ± 67 with $\Xi_c \rightarrow \Xi e^+ \nu$ feedthrough, and 398 ± 58 with e fake background. The sidebands of the $p\pi^-$ invariant mass distribution are used to estimate the fake Λ background. The background from $\Xi_c \rightarrow \Xi e^+ \nu$ decays is estimated using the result of a previous CLEO analysis [11].

The normalization and momentum spectrum of the e fake background is estimated using the wrong sign (WS) $h^+\bar{\Lambda}$ data sample (no charge conjugation is implied), where h^+ and $\bar{\Lambda}$ satisfy all analysis selection criteria. The h^+ tracks in this sample are mostly fakes as there are few processes contributing $e^+\bar{\Lambda}$ pairs after the selection criteria are applied. If no particle identification is used for h , the probability to find a ($h^+\bar{\Lambda}$ or $h^-\Lambda$) WS or ($h^+\Lambda$ or $h^-\bar{\Lambda}$) RS pair is approximately equal because the net charge of the event is zero. The equality is not perfect due to (a) baryon conservation: a Λ is more likely to be produced with an antiproton in WS rather than RS combinations, and (b) associated strangeness production: there is a higher fraction of kaons in RS rather than WS combinations. When the particle identification requirements for h are applied, the importance of these correlations is magnified by the high e fake rates of antiprotons and kaons. Therefore, antiprotons are excluded by using only one WS charge conjugate state ($h^+\bar{\Lambda}$), and the momentum

region where the e fake rate from kaons is high is excluded by requiring $|\vec{p}_e| > 0.7 \text{ GeV}/c$. Differences that remain between the momentum spectra and particle species of hadronic tracks in $h^+\bar{\Lambda}$ and in $h^+\Lambda$ and $h^-\bar{\Lambda}$ combinations are second order and are accounted for by a systematic uncertainty.

Calculating kinematic variables requires knowledge of the Λ_c^+ momentum, which is unknown due to the undetected neutrino. The direction of the Λ_c^+ is approximated using the information provided by the thrust axis of the event and the kinematic constraints of the decay. The magnitude of the Λ_c^+ momentum is obtained as a weighted average of the roots of the quadratic equation $\vec{p}_{\Lambda_c^+}^2 = (\vec{p}_\Lambda + \vec{p}_e + \vec{p}_\nu)^2$. The weights are assigned based on the measured fragmentation function of Λ_c^+ . After the Λ_c^+ momentum is estimated, the four kinematic variables are easily obtained. The kinematic variables $t \equiv q^2/q_{\text{max}}^2$, $\cos\theta_\Lambda$, $\cos\theta_w$, and χ achieve resolutions of 0.2, 0.3, 0.2, and 45° , respectively.

A four-dimensional maximum likelihood fit in a manner similar to Ref. [12] is performed in the space of t , $\cos\theta_\Lambda$, $\cos\theta_w$, and χ . The technique makes possible a multidimensional fit to variables modified by experimental acceptance and resolution taking into account correlations among the variables. We have performed two types of fit. The first fit is unbinned in all four dimensions. The second fit is unbinned in $\cos\theta_\Lambda$, $\cos\theta_w$, and χ and binned in t . While both fits produce consistent results, the second fit is used for the main result because it allows the estimation of a systematic uncertainty associated with the modeling of the t distribution.

The signal probability density function for the likelihood function is estimated at each data point using signal Monte Carlo (MC) events, generated according to the HQET consistent KK model with a GEANT based simulation [13], by sampling the MC distribution at the reconstructed level in a search volume around the data point. The choice of the volume size depends on the systematic effect from finite search volumes, the resolution of each kinematic variable, and the finite size of the MC samples used as input to the fitter. Sufficiently large MC samples are generated to allow the size of each dimension of the search volume to equal the measured resolution in that dimension and to ensure that each search volume has sufficient MC events that all data points can be retained in the fit. For the fit binned in t , 20 bins are used. The background probability density functions are modeled similarly using samples of events for each background component. The e fake background is modeled using a sample of events collected for that purpose from the data. Feedthrough background from $\Xi_c \rightarrow \Xi e^+ \nu$ is modeled by the MC sample generated according to the HQET consistent KK model. Fake Λ background is modeled using the data events in the sidebands of the $p\pi^-$ invariant mass distribution. For the binned part of the fit, the above distributions are projected

onto t and binned. The background normalizations are fixed in the fits to the measured values.

Using the above method, a simultaneous fit for the form factor ratio and the pole mass is made. We find $R = -0.31 \pm 0.05(\text{stat})$ and $M_{\text{pole}} = [2.21 \pm 0.08(\text{stat})] \text{ GeV}/c^2$. This is the main result of the analysis. Figures 1 and 2 show the t , $\cos\theta_\Lambda$, $\cos\theta_W$, and χ projections for the data and fit.

We have considered the following sources of systematic uncertainty and give our estimate of their magnitude in parentheses for R and M_{pole} , respectively. The uncertainty associated with the size of the search volume and a possible bias in the fit is measured from a statistical experiment in which a set of mock data samples, including signal and all background components, was fit in the same way as the data (0.006, 0.048) [14]. The uncertainty due to the limited size of the signal MC sample is estimated by dividing the sample into four independent equal subsamples and repeating the fit (0.007, 0.012). The uncertainty due to background normalizations is determined by varying the estimated number of background events by 1 standard deviation separately for each type of background (0.023, 0.024). The uncertainty associated with the modeling of the background shapes, including uncertainties originating from the modeling of the e fake background, and the unknown form factor ratio and M_{pole} for the decays $\Xi_c \rightarrow \Xi e^+ \nu$, is estimated by varying these shapes or by using alternative background samples (0.024, 0.049). The uncertainty due to the small background contribution of random Λe^+ pairs from the continuum ($e^+e^- \rightarrow q\bar{q}$) and $Y(4S) \rightarrow B\bar{B}$ events, which

are not modeled in the fit, is obtained from a generic MC sample and is estimated by repeating the fit with and without this background (0.013, 0.038). The modes $\Lambda_c^+ \rightarrow \Lambda X e^+ \nu$, where X represents additional decay products, have never been observed. The current upper limit is $\frac{B(\Lambda_c^+ \rightarrow \Lambda X e^+ \nu)}{B(\Lambda_c^+ \rightarrow \Lambda e^+ \nu)} < 0.15$, where $X \neq 0$, at 90% confidence level [9]. The uncertainty due to the presence of these modes is estimated from a series of fits, each having an additional background component with floating normalization to represent a $\Lambda_c^+ \rightarrow \Lambda X e^+ \nu$ mode. The uncertainty due to the possible presence of $\Lambda_c^+ \rightarrow \Lambda X e^+ \nu$ is assigned as the largest deviation from the main result found in these fits (0.022, 0.091). The uncertainty associated with the Λ_c^+ fragmentation function is estimated by varying this function (0.003, 0.002). The uncertainty related to MC modeling of the reconstruction efficiency of slow pions produced in Λ decays is obtained by varying this efficiency according to our understanding of the CLEO detector (0.004, 0.003). For approximately 10% of the data near the end of the CLEO II.V data taking period, the t distribution for $t > 0.8$ is mismodeled in the MC simulation, while the other kinematic variables are well described. The effect of this mismodeling was determined by binning the data in t and performing a series of fits with a variable range of t excluded. The size of the systematic uncertainty is conservatively taken to be the largest difference between the results of these fits and the main result (0.004, 0.072). The simulation used to obtain the main result does not include final state radiation. The systematic uncertainty due to this is determined as the difference between the result of a fit where electroweak radiative corrections have been modeled [15] and the main result (0.005, 0.009).

Adding all sources of systematic uncertainty in quadrature, the final result is $R = -0.31 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$

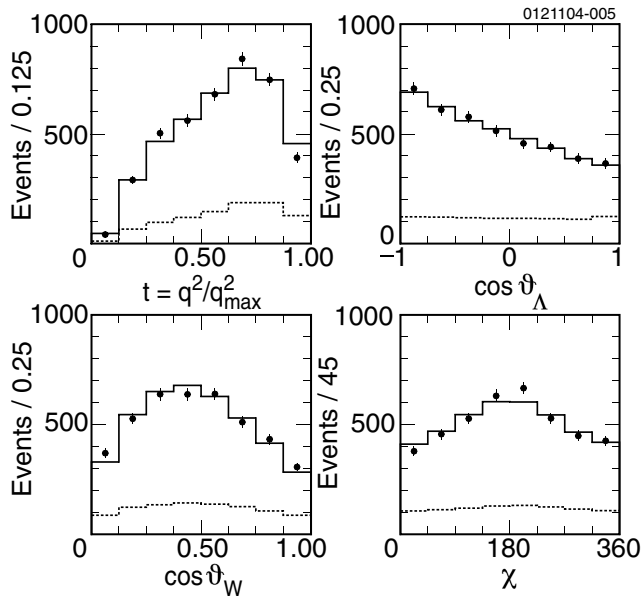


FIG. 1. Projections of the data (points with statistical error bars) and the fit (solid histogram) onto t , $\cos\theta_\Lambda$, $\cos\theta_W$, and χ . The dashed lines show the sum of the background distributions.

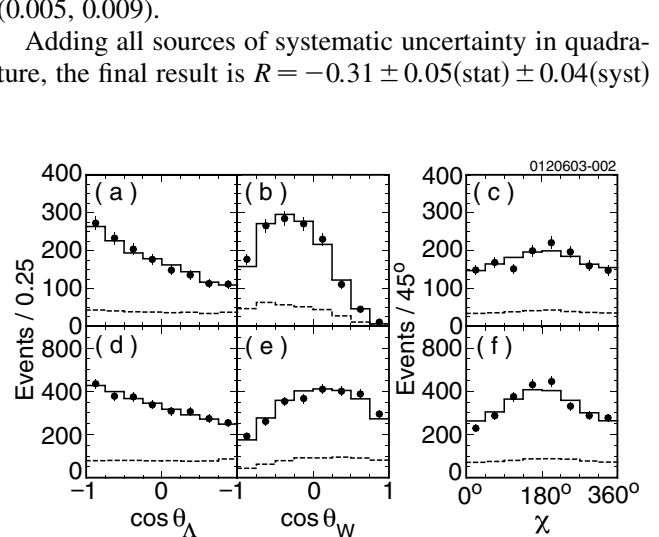


FIG. 2. Projections of the data (points with statistical error bars) and the fit (solid histogram) onto $\cos\theta_\Lambda$, $\cos\theta_W$, and χ for two t regions. The plots labeled (a)–(c) are for $t < 0.5$; (d)–(f) are for $t > 0.5$. The dashed lines show the sum of the background distributions.

and $M_{\text{pole}} = [2.21 \pm 0.08(\text{stat}) \pm 0.14(\text{syst})] \text{ GeV}/c^2$, the latter value being consistent with vector dominance. We also find $R = -0.35 \pm 0.04(\text{stat}) \pm 0.04(\text{syst})$ from a fit with $M_{\text{pole}} = m_{D_s^*}$. Using the values of R and M_{pole} obtained in the simultaneous fit and the KK model, the mean value of the decay asymmetry parameter of $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ [16] averaged over charge conjugate states is calculated to be $\alpha_{\Lambda_c} = -0.86 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$, for $\langle q^2 \rangle = 0.67 \text{ (GeV}/c^2)^2$.

In the standard model, CP violation is expected to be small in semileptonic decays and absent in the decay $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$. If CP is conserved, the following relation is satisfied:

$$\frac{d\Gamma(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e)}{dq^2 d\cos\theta_\Lambda d\cos\theta_W d\chi} = \frac{d\Gamma(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} e^- \bar{\nu}_e)}{dq^2 d\cos\theta_\Lambda d\cos\theta_W d(-\chi)},$$

Following [17] and by extension, a CP -violating asymmetry of the Λ_c^+ is defined as $\mathcal{A}_{\Lambda_c} = \frac{(\alpha_{\Lambda_c} + \alpha_{\bar{\Lambda}_c})}{(\alpha_{\Lambda_c} - \alpha_{\bar{\Lambda}_c})}$. In the KK model, the angular distributions for Λ_c^+ and $\bar{\Lambda}_c^-$ are governed by R and M_{pole} . From the values of R and M_{pole} obtained in a simultaneous fit to each charge conjugate state separately and the KK model we calculate $\alpha_{\Lambda_c} \alpha_\Lambda = -0.561 \pm 0.026(\text{stat})$ and $\alpha_{\bar{\Lambda}_c} \alpha_{\bar{\Lambda}} = -0.544 \pm 0.024(\text{stat})$. Using $\frac{\alpha_{\Lambda_c} \alpha_\Lambda - \alpha_{\bar{\Lambda}_c} \alpha_{\bar{\Lambda}}}{\alpha_{\Lambda_c} \alpha_\Lambda + \alpha_{\bar{\Lambda}_c} \alpha_{\bar{\Lambda}}} = \mathcal{A}_{\Lambda_c} + \mathcal{A}_\Lambda$, which is valid to first order in \mathcal{A}_Λ and \mathcal{A}_{Λ_c} , we obtain $\mathcal{A}_{\Lambda_c} = 0.00 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02$, where in the systematic uncertainty the correlations among the systematic uncertainties for the charge conjugate states are taken into account and the third error is from the uncertainty in \mathcal{A}_Λ .

In conclusion, using a four-dimensional maximum likelihood fit, the angular distributions of $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ have been studied. We find $R = -0.31 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$ and $M_{\text{pole}} = [2.21 \pm 0.08(\text{stat}) \pm 0.14(\text{syst})] \text{ GeV}/c^2$. This is the most precise measurement of R , and it demonstrates that f_2 is nonzero with a combined statistical and systematic significance exceeding 4σ . This is also the first measurement of M_{pole} in a charm baryon semileptonic decay. Our measurement is consistent with vector dominance. These results correspond to $\alpha_{\Lambda_c} = -0.86 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$, for $\langle q^2 \rangle = 0.67 \text{ (GeV}/c^2)^2$. Comparing the angular distributions for Λ_c^+ and $\bar{\Lambda}_c^-$, no evidence for CP violation is found: $\mathcal{A}_{\Lambda_c} = 0.00 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02(\mathcal{A}_\Lambda)$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, by the U.S. Department of Energy,

by the Research Corporation, and by the Texas Advanced Research Program.

-
- [1] S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004).
- [2] N. Isgur and M.B. Wise, Phys. Lett. B **232**, 113 (1989); **237**, 527 (1990); E. Eichten and B. Hill, Phys. Lett. B **234**, 511 (1990); H. Georgi, Phys. Lett. B **240**, 447 (1990).
- [3] T. Mannel, W. Roberts, and Z. Ryzak, Nucl. Phys. **B355**, 38 (1991); Phys. Lett. B **255**, 593 (1991); F. Hussain, J. G. Körner, M. Krämer, and G. Thompson, Z. Phys. C **51**, 321 (1991); A. F. Falk and M. Neubert, Phys. Rev. D **47**, 2982 (1993); H. Georgi, B. Grinstein, and M.B. Wise, Phys. Lett. B **252**, 456 (1990); N. Isgur and M.B. Wise, Nucl. Phys. **B348**, 276 (1991); H. Georgi, Nucl. Phys. **B348**, 293 (1991).
- [4] J.G. Körner and M. Krämer, Phys. Lett. B **275**, 495 (1992).
- [5] The sign of the interference term (the term containing $\cos\chi$) in Ref. [4] has been corrected in Eq. (2) with the approval of the authors of Ref. [4] (private communication).
- [6] Y. Kubota *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).
- [7] T. Hill, Nucl. Instrum. Methods Phys. Res., Sect. A **418**, 32 (1998).
- [8] G.L. Crawford *et al.* (CLEO Collaboration), Phys. Rev. Lett. **75**, 624 (1995).
- [9] T. Bergfeld *et al.* (CLEO Collaboration), Phys. Lett. B **323**, 219 (1994).
- [10] G.C. Fox *et al.*, Phys. Rev. Lett. **41**, 1581 (1978).
- [11] J. Alexander *et al.* (CLEO Collaboration), Phys. Rev. Lett. **74**, 3113 (1995).
- [12] D.M. Schmidt, R.J. Morrison, and M.S. Witherell, Nucl. Instrum. Methods Phys. Res., Sect. A **328**, 547 (1993).
- [13] R. Brun *et al.*, GEANT 3.15, CERN Report No. DD/EE/84-1, 1987.
- [14] The stability of the fit with respect to the size of the search volume was studied by repeating the fit with search volumes increased or decreased by up to a factor of 4. For both R and M_{pole} the results vary by no more than one-fifth of the statistical uncertainty.
- [15] E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994); D. Atwood and W. Marciano, Phys. Rev. D **41**, R1736 (1990).
- [16] The decay asymmetry parameter α_{Λ_c} is defined as [4] $\alpha_{\Lambda_c} = \frac{|H_{1/2,1}|^2 - |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 - |H_{-1/2,0}|^2}{|H_{1/2,1}|^2 + |H_{-1/2,-1}|^2 + |H_{1/2,0}|^2 + |H_{-1/2,0}|^2}$.
- [17] J.F. Donoghue, and S. Pakvasa, Phys. Rev. Lett. **55**, 162 (1985). A CP -violating parameter, \mathcal{A}_Λ , for $\Lambda \rightarrow p\pi^-$ is defined as $\mathcal{A}_\Lambda \equiv \frac{(\alpha_\Lambda + \alpha_{\bar{\Lambda}})}{(\alpha_\Lambda - \alpha_{\bar{\Lambda}})}$. \mathcal{A}_Λ is measured to be $\mathcal{A}_\Lambda = 0.012 \pm 0.021$ [1].