Observation of the Decay $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$

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Using the CLEO detector at the Cornell Electron Storage Ring we have observed the Ω_c^0 (*css* ground state) in the decay $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$. We find a signal of 11.4 ± 3.8(stat) events. The probability that we have observed a background fluctuation is 7.6×10^{-5}. We measure $B(\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e) \cdot \sigma(e^+ e^- \rightarrow \Omega_c^0 X) = (42.2 \pm 14.1(\mathrm{stat}) \pm 5.7(\mathrm{syst}))$ fb and $R = \frac{\Gamma(\Omega_c^0 \rightarrow \Omega^- \pi^+)}{\Gamma(\Omega_c^0 \rightarrow \Omega^- e \nu_e)} = 00.41 \pm 0.19(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. This is the first statistically significant observation of an individual decay mode of the Ω_c^0 in $e^+ e^-$ annihilation and the first example of a baryon decaying via β emission, where no quarks from the first generation participate in the reaction.

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The transition rate for charm quark semileptonic decays is determined by the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cd}|$ and $|V_{cs}|$ and heavy quark form factors. Since both $|V_{cd}|$ and $|V_{cs}|$ are known from three generation unitarity, measurements of charm semileptonic decays allow an absolute measurement of the form factors [1].

Within heavy quark effective theory (HQET) [2], Λ-type baryons are more straightforward to treat than mesons as they consist of a heavy quark and a spin and isospin zero light diquark. This simplicity allows for more reliable predictions for heavy quark to light-quark transitions [3] than in the case for mesons. For example, the measurement of the form factors in $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$ aids the future determination of $|V_{ub}|$ and $|V_{cb}|$ using Λ_b^0 decays since HQET relates the form factors in Λ_c^+ decay to those governing Λ_b^0 decays.

However, it is important to test the theoretical treatment of charm baryon semileptonic decays. In this Letter we report the first observation of $\Omega_c^0 \to \Omega^- e^+ \nu_e$. The Ω_c^0 ($c\{ss\}$) is a $J^P = 1/2^+$ ground state baryon, where $\{ss\}$ denotes the symmetric nature of its wave function with respect to the interchange of the light-quark spins. As $\Omega_c^0 \to \Omega^- e^+ \nu_e$ is a $J^P = 1/2^+ \to 3/2^+$ transition, it is sensitive to additional form factors not present in $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$, and so provides new information to test theory [4].

The data sample used in this analysis was collected with CLEO II [5] and the upgraded CLEO II.V [6] detector operating at the Cornell Electron Storage Ring (CESR). The integrated luminosity consists of 13.75 fb^{-1} taken at and just below the $\Upsilon(4S)$ resonance corresponding to approximately $e^+e^- \to c\bar{c}$ events. The Monte Carlo (MC) simulated signal events were generated for the two detector configurations using a GEANT-based [7] simulation and were processed similarly to the data. We take $m_{\Omega_c^0} = 2704.0\ \text{MeV}/c^2$ [1]. For $\Omega_c^0 \to \Omega^- e^+ \nu_e$ we assume no net polarization of the Ω^- [8]. The fragmentation function for the Ω_c^0 is unknown; therefore, the measured fragmentation function of the Ξ_c [9] is used. Throughout this paper charge conjugate states are implicitly included, and we use the symbol e to denote an electron or positron.

We search for the decay $\Omega_c^0 \to \Omega^- e^+ \nu_e$ in $e^+e^- \to c\bar{c}$ events by detecting an $\Omega^- e^+$ (right sign) pair with invariant mass $m_{\Omega^- e^+} < m_{\Omega_c^0}$. The technique is very similar to that used in previous CLEO analyses of $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$, $\Xi_c^0 \to \Xi^- e^+ \nu_e$, and $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ [10–12].

Positrons are identified using a likelihood function that incorporates information from the calorimeter and dE/dx systems. We require the e^+ to satisfy $|\cos\theta| < 0.71$, where θ is the angle between the e^+ momentum and the beam line. The e^+ is also required to originate from the primary vertex and have a momentum greater than 0.5 GeV/c. Muons are not used as $\Omega_c^0 \to \Omega^- l^+ \nu_l$ produces predominantly low momentum leptons and the CLEO muon identification system is not efficient below 1 GeV/c.

The Ω^- is reconstructed in the decay $\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p^+ \pi^-$. The analysis procedure for reconstructing these particles closely follows that presented elsewhere [10–14]. Kaon and proton candidates must have specific ionization and time-of-flight measurements consistent with the expected values. Particle identification is not used for pions. The hyperons are required to have vertices well separated from the beam spot, with the flight distance of the secondary Λ^0 greater than that of the Ω^-. The Ω^- is required to originate from the primary vertex of the event. To reduce background in Ω^- reconstruction, kaons and Λ^0's consistent with originating from the primary vertex are excluded. In order to improve mass resolution in the Ω^- reconstruction, the mass of the Λ^0 candidate was kinematically constrained to the world average Λ^0 mass.

Figure 1 shows the invariant mass distribution of $\Lambda^0 K^-$ pairs with all Ω^- finding selection criteria imposed. The signal is fit by a Gaussian and the background is parametrized by a second order polynomial function. The signal yield from the fit is 763 ± 32. The mean and width of the Gaussian are $1672.50 \pm 0.07\ \text{MeV}/c^2$ and $1.44 \pm 0.06\ \text{MeV}/c^2$, respectively. This width is consistent with that expected from MC simulation.

The Ω^- candidates are combined with e's and the invariant mass of the $\Omega^- e$ pair is required to satisfy $m_{\Omega^- e} < m_{\Omega_c^0}$. We require $|\vec{p}_{\Omega^-} + \vec{p}_e| > 1.4\ \text{GeV}/c$ to reduce background from $B\bar{B}$ events. Figure 2 shows the invariant mass distributions of $\Lambda^0 K^-$ pairs in events that contain (a) a right sign (RS) lepton that is an e^+, and (b) a wrong sign (WS) lepton that is an e^-. There is a pronounced excess of RS events compared to WS events at the Ω^- mass, as would be expected if we are observing the decay $\Omega_c^0 \to \Omega^- e^+ \nu_e$. The $\Lambda^0 K^-$ invariant mass distributions are fit with a function consisting of a Gaussian with width determined by MC simulation

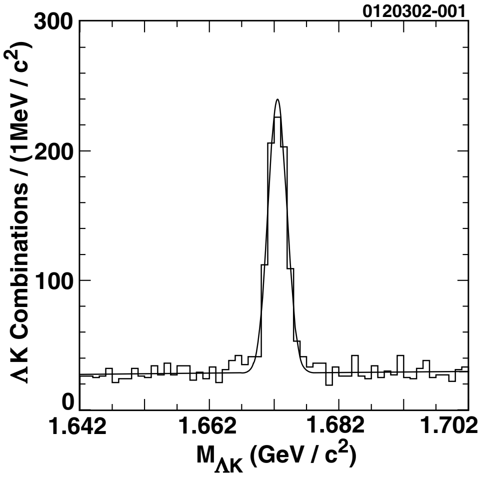

FIG. 1. Invariant mass of $\Lambda^0 K^-$ combinations.

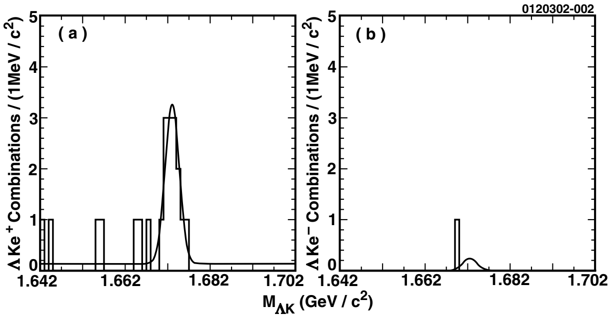

FIG. 2. The invariant mass of $\Lambda^0 K^-$ pairs for events with (a) an e^+ (that is, RS events) and (b) an e^- (that is, WS events) satisfying the selection criteria described in the text.

(1.66 MeV/c^2) to represent the signal and a first order polynomial function to represent the background. In the fit to the WS distribution the mean of the Gaussian is fixed to the world average Ω^- mass. We define the signal region as a $\pm 3.0\sigma$ interval around the Ω^- mass. The fit to the RS distribution returns 13.0 ± 3.8 (1.3 ± 0.6) events in the Gaussian component (background component) in the signal region.

There are five types of background that may produce events that populate the signal region. These are (1) fake e–real Ω^- combinations, (2) random $\Omega^- e$ pairs from (a) the continuum (generic $e^+e^- \to q\bar{q}$ events), where the Ω^- is not a decay product of a charm baryon semileptonic decay, and (b) B decays from $\Upsilon(4S)$ events, (3) feed-down from decays of the type $\Omega_c^0 \to \Omega^- X e^+ \nu_e$, where X is an unobserved decay product, (4) feedthrough from $\Xi_c \to \Omega^- K e^+ \nu$ decays, (5) combinatorial background to the Ω^- (usually a Λ^0 with a random kaon) from (a) coherent background from the semileptonic decays $\Xi_c \to \Xi e^+ \nu$ and $\Lambda^+ \to \Lambda^0 e^+ \nu$ and (b) all other sources of fake Ω^- baryons. The combinatorial background to the Ω^- (5) does not peak at the Ω^- mass; therefore, the population of events outside the signal region can be used to check estimates of the number of background events in the signal region. The background from types (1), (2), and (5b) populates both RS and WS $\Lambda^0 K^-$ invariant mass distributions. Below we describe how the backgrounds to the signal region were evaluated. In order to gain confidence in our results, we also obtained estimates of the expected number of background events for the RS distribution outside the signal region and for the WS distribution inside and outside the signal region. The results of the background study are summarized and compared to the data.

The fake e contribution depends on the particle populations in $c\bar{c}$ jets containing an Ω^-, and the species and momentum-dependent fake rate [15]. In this analysis, strangeness (baryon number) conservation leads to enhanced kaon (antiproton) production in $e^+e^- \to \Omega^- X$ events. Antiprotons and kaons have larger e fake rates than pions. Because of baryon number conservation, fake leptons from baryons are much more numerous in WS than in RS combinations. To account for the different e fake rates of each particle species, all tracks in events containing an Ω^- that are not positively identified as e's are weighted by the momentum-dependent e fake rates for each particle species, and the particle populations in $c\bar{c}$ jets containing an Ω^-, determined from data. We estimate there are 1.4 ± 0.4 (0.2 ± 0.2) fake e^+–real Ω^- RS events due to kaons and protons (pions) faking e^+ in the signal region. Thus, the total contribution from this source [background type (1)] is 1.6 ± 0.5 RS events.

The Ω^- production mechanisms in continuum events and $\Upsilon(4S) \to B\bar{B}$ decays are not well known. Therefore, MC estimation of random combinations of real $\Omega^- e$ pairs from these processes will be unreliable. However, previous CLEO analyses found that the background from random $\Lambda^0 e$ and Ξe pairs in the modes $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$, $\Xi_c^0 \to \Xi^- e^+ \nu_e$, and $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ is small and is likely to populate both RS and WS equally [10–12]. In this analysis the absence of WS events at the Ω^- mass demonstrates that the random pairing of an Ω^- and an e is negligible. We assume, therefore, that this is also true for the background from this source [background type (2)] in the RS events.

Background due to decays of the type $\Omega_c^0 \to \Omega^- X e^+ \nu_e$, for example, $\Omega_c^0 \to \Omega^{*-} e^+ \nu_e$, $\Omega^{*-} \to \Omega^- X$, produces a peak in the $\Lambda^0 K^-$ mass distribution. The lightest and best understood resonance in the Ω^- family is the $\Omega(2250)^-$ [1], but this does not decay to an Ω^-. The $\Omega(2470)^-$ decays to $\Omega^- \pi^+ \pi^-$; however, because the mass of this resonance is close to the Ω_c^0 mass, the phase space suppression will be severe, and the e^+ spectrum entirely below 0.5 GeV/c. We note that due to isospin conservation the decay $\Omega^{*-} \to \Omega^- \pi^0$ is forbidden. If a yet-to-be-discovered Ω^{*-} with a mass in the range $m_{\Omega^-} + 2m_\pi < m_{\Omega^{*-}} < 2.250$ GeV/c^2 exists, it could, in principle, constitute a background to this analysis through the decay $\Omega^{*-} \to \Omega^- (\pi\pi)^0$. However, it is likely that the dominant decay would be $\Omega^{*-} \to \Xi K$, which has a larger phase space available. Given that no light Ω^{*-} has been identified, we do not consider this possibility further. We conclude that the background due to $\Omega_c^0 \to \Omega^- X e^+ \nu_e$ [background type (3)] is negligible.

The modes $\Xi_c^+ \to \Omega^- K^+ e^+ \nu_e$ and $\Xi_c^0 \to \Omega^- K^0 e^+ \nu_e$ also produce a peak in the $\Lambda^0 K^-$ mass distribution. However, these decays are expected to be suppressed for the following reasons. Semileptonic decays favor little hadronic fragmentation. A study of $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$ [10] found that $B(\Lambda_c^+ \to \Lambda^0 e^+ \nu_e)/B(\Lambda_c^+ \to \Lambda^0 X e^+ \nu_e) > 0.85$ at 90% confidence level. The same pattern is seen in charm mesons [16]. In B meson semileptonic decays, where the energy release is larger, there is only modest nonresonant production [1]. Also, $\Xi_c \to \Omega^- K e^+ \nu_e$ proceeds via the creation of an $s\bar{s}$ pair from the vacuum, which is suppressed relative to light-quark antiquark pair creation from the vacuum. There is no experimental evidence for $s\bar{s}$ pair creation in semileptonic decays of b and c quarks. In addition, as $\Xi_c \to \Omega^- K e^+ \nu_e$ produces softer leptons than $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$, the reconstruction efficiency is an order of magnitude lower, and $M_{\Omega^- e^+} < 1.98\ \mathrm{GeV}/c^2$ is satisfied. Figure 3 shows the $\Omega^- e^+$ invariant mass distribution for events in the signal region and compares it to the distribution expected for $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$. The simulation is consistent with the data. There is one event with $M_{\Omega^- e^+} < 1.98\ \mathrm{GeV}/c^2$ consistent with $\Xi_c \rightarrow \Omega^- K e^+ \nu_e$. As this event could be either signal or background, it contributes a 0^{+1}_{-0} event uncertainty to the number of signal events, and this comprises the total contribution to our signal from background of type (4).

Feedthrough from other charm baryon semileptonic decays, $\Lambda_c^+ \rightarrow \Lambda^0 e^+ \nu_e$, $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$, and $\Xi_c^+ \rightarrow \Xi^0 e^+ \nu_e$ (coherent background), is a source of $\Lambda^0 e^+$ pairs, which, when combined with a random track in the event satisfying the kaon hypothesis, can mimic the signal. Since the e^+e^- cross section for each process has been measured [10–12], a reliable prediction of the coherent background based on MC simulation can be made [17]. We estimate that the coherent background [type (5a)] contributes 3.5 ± 1.9 RS events distributed uniformly in the range $1.642 < m_{\Lambda^0 K^-} < 1.702\ \mathrm{GeV/c^2}$.

We now compare our estimate of the RS and WS backgrounds to the data. We estimate that fake e background contributes 0.3 ± 0.3 (0.4 ± 0.4) WS events in the signal region (outside the signal region). The sum is in good agreement with the one WS event observed. We estimate coherent backgrounds (fake e^+–fake Ω^-) contribute 2.9 ± 1.6 (1.6 ± 0.5) RS events outside the signal region in reasonable agreement with the seven RS events observed outside the signal region. The slight excess observed in data may be attributed to additional sources of fake Ω^-'s [background (5b)] that have not been accounted for. However, the excess, being a part of the fake Ω^- background, is accounted for in determining the signal yield by fitting the $\Lambda^0 K^-$ mass. Finally, we estimate that the coherent background (fake e^+–fake Ω^-) contributes 0.6 ± 0.3 (0.3 ± 0.1) events in the signal region in good agreement with the 1.3 ± 0.6 background events in the polynomial component in the signal region returned from the fit.

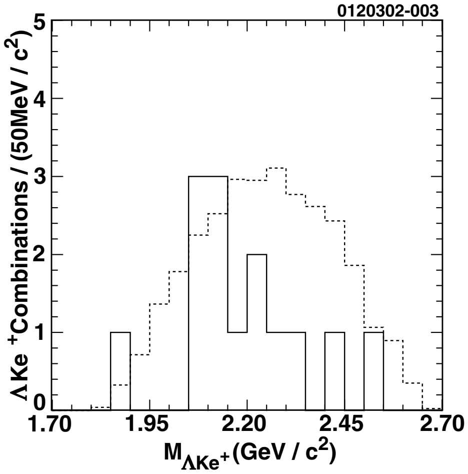

FIG. 3. $\Omega^- e^+$ invariant mass distribution for events in the signal region (solid line) and Monte Carlo simulation (dashed line).

To estimate the number of signal events in the signal region, we subtract the fake e background from the Gaussian component of the fit to obtain 11.4 ± 3.8 events consistent with $\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$. The probability for the background in the signal region (i.e., the sum of the fake Ω^- background in the signal region and the fake e^+–real Ω^- background) to fluctuate to 14 or more events is 2.3×10^{-6}. Correcting the number of signal events by the signal efficiency and integrated luminosity of the data sample, our measured $B(\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e) \cdot \sigma(e^+e^- \rightarrow \Omega_c^0 X)$ is (42.2 ± 14.1 ± 5.7) fb.

We have considered the following sources of systematic uncertainty and give our estimate of their magnitude in parentheses. Background from the process $\Xi_c \rightarrow \Omega^- K e^+ \nu_e$ is estimated from the $\Omega^- e^+$ invariant mass distribution of Fig. 3 (7.1%). The uncertainty in the fake e background is determined from our knowledge of the species and momentum-dependent fake rates and particle populations in $c\bar{c}$ jets containing an Ω^- (6.7%). The uncertainty associated with imperfect knowledge of the Ω_c^0 fragmentation function is estimated by varying this function (6.0%). The uncertainty associated with the baryon finding efficiency is determined by data and MC studies for the Ω^- and Λ^0 to be 5.0% and 4.0%, respectively. This uncertainty includes the uncertainty associated with track finding efficiency for p, π, and K. The uncertainty in finding the e track is determined by our knowledge of the track finding efficiency of the CLEO II/II.V detectors (1.0%). The uncertainty associated with the e identification efficiency is determined by Bhabha embedding studies (2.0%). The uncertainty associated with MC modeling of long-lived hyperons is estimated to be 2.0%. The uncertainty associated with MC modeling of slow pions from Λ^0 decays is obtained by varying the slow pion finding efficiency according to our understanding of the CLEO detector (1.2%). There is a 1.0% systematic uncertainty in the total integrated luminosity. The uncertainty in $B(\Omega^- \rightarrow \Lambda^0 K^-)$ and $B(\Lambda^0 \rightarrow p^+ \pi^-)$ contribute a 1.3% uncertainty to our measurement. Finite MC statistics contribute a 0.1% uncertainty to the signal efficiency. The uncertainty in the efficiency associated with the choice of model for the decay is estimated by comparing the efficiency with a matrix element producing Ω^-'s with no net polarization (which is the efficiency used for the result) and full polarization. The difference in reconstruction efficiency for the two models is negligible, and no uncertainty is assigned from this source. Adding all sources of systematic uncertainty in quadrature, the total systematic uncertainty is found to be 13.6%.

We compute the combined statistical and systematic significance of our observation by the following procedure. Most of the quantities for which a systematic uncertainty has been assigned do not contribute to the uncertainty in the magnitude of the background; the exceptions are the uncertainties associated with $\Xi_c \to \Omega^- K e^+ \nu_e$ and fake e background. We assume the event satisfying $M_{\Omega^- e^+} < 1.98\ \mathrm{GeV}/c^2$ is background from $\Xi_c \to \Omega^- K e^+ \nu_e$ and increase the background by one event. We also increase the background by our uncertainty in the fake e background. Taking account of these systematic uncertainties, the probability for the background to fluctuate to 14 or more events in the RS signal is 7.6×10^{-5}.

At present there is no reliable normalization of the Ω_c^0 branching ratios. As the rates for semileptonic decays are, in principle, simpler to calculate than hadronic decays, the ratio of our $\mathcal{B} \cdot \sigma$ to that for a hadronic mode will be useful for normalizing the hadronic scale once reliable theoretical predictions exist for the semileptonic modes. Therefore, we measure $R = \Gamma(\Omega_c^0 \to \Omega^- \pi^+)/\Gamma(\Omega_c^0 \to \Omega^- e^+ \nu_e)$. We search for $\Omega_c^0 \to \Omega^- \pi^+$ using a set of selection criteria very similar to those in the $\Omega_c^0 \to \Omega^- e^+ \nu_e$ analysis [18]. We find 14.1 ± 4.3 events consistent with the decay $\Omega_c^0 \to \Omega^- \pi^+$ [19]. After correcting the yields by the efficiencies, we compute $R = \Gamma(\Omega_c^0 \to \Omega^- \pi^+)/\Gamma(\Omega_c^0 \to \Omega^- e^+ \nu_e) = 0.41 \pm 0.19(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. Most of the systematic uncertainties cancel in forming the ratio. The largest remaining sources of systematic uncertainty are associated with the estimates of background for the semileptonic mode. The corresponding ratio in Λ_c^+ (Ξ_c^0) decays is $0.44 \pm 0.09(\mathrm{stat})$ [$0.3 \pm 0.1(\mathrm{stat{+}syst})$].

In summary, we have reconstructed 14 $\Omega^- e^+$ pairs of which 11.4 ± 3.8 are consistent with the decay $\Omega_c^0 \to \Omega^- e^+ \nu_e$. The probability that we have observed a background fluctuation is 7.6×10^{-5}. Our measured $\mathcal{B} \cdot \sigma$ is $(42.2 \pm 14.1 \pm 5.7)$ fb. This is the first statistically significant observation of an individual decay mode of the Ω_c^0 in e^+e^- annihilation and the first example of a baryon decaying via β emission, where no quarks from the first generation participate in the reaction. We have also measured $R = \Gamma(\Omega_c^0 \to \Omega^- \pi^+)/\Gamma(\Omega_c^0 \to \Omega^- e^+ \nu_e) = 0.41 \pm 0.19 \pm 0.04$.

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[18] For $\Omega_c^0 \to \Omega^- \pi^+$ we require $x_p = |\vec{p}_{\Omega^- \pi}|/\sqrt{E_{\mathrm{beam}}^2 - M_{\Omega_c^0}^2} > 0.5$.

[19] The $\Omega_c^0 \to \Omega^- \pi^+$ yield in this analysis is consistent with that reported in [13].