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

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Abstract

Using the CLEO detector at the Cornell Electron Storage Ring we have observed the Ω_c^0 (css ground state) in the decay $\Omega_c^0 \to \Omega^- e^+ \nu_e$. 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 $B(\Omega_c^0 \to \Omega^- e^+ \nu_e) \cdot \sigma(e^+ e^- \to \Omega_c^0 X) = (42.2 \pm 14.1(\text{stat}) \pm 5.7(\text{syst}))$ fb and $R = \frac{\Gamma(\Omega_c^0 \to \Omega^- \pi^+)}{\Gamma(\Omega_c^0 \to \Omega^- e \nu_e)} = 0.41 \pm 0.19(\text{stat}) \pm 0.04(\text{syst})$. 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 18 million $e^+e^- \to c\bar{c}$ events.

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 in the range $m_{\Omega^-} < m_{\Omega^- e^+} < m_{\Omega_c^0}$ [7]. 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 $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ [8–10].

Positrons are identified using a likelihood function which incorporates information from the calorimeter and dE/dx systems. We require the positron to satisfy $|\cos\theta| < 0.71$ where θ is the angle between the positron momentum and the beam line. A positron 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 [8–12]. 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 Λ^0 mass constraint is employed.

The Monte Carlo (MC) simulated signal events used in this analysis were generated for the two detector configurations using a GEANT-based [13] simulation and were processed similarly to the data. We take $m_{\Omega_c^0} = 2704.0$ MeV/c^2 [1]. For $\Omega_c^0 \to \Omega^- e^+ \nu_e$ we assume no net polarization of the Ω^- [14]. The fragmentation function for the Ω_c^0 is unknown, therefore the measured fragmentation function of the Ξ_c [15] is used.

Figure 1 shows the invariant mass distribution of $\Lambda^0 K^-$ pairs with all selection criteria imposed. The signal is fit by a Gaussian and the background is parameterized 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 ± 0.07 MeV/c^2 and is 1.44 ± 0.06 MeV/c^2 respectively. The width is consistent with that expected from MC simulation.

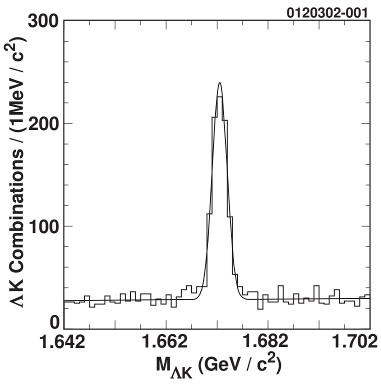

FIG. 1. Invariant mass of $\Lambda^0 K^-$ combinations.

The Ω^- candidates are combined with positrons. The invariant mass of the $\Omega^- e^+$ pair is required to satisfy $m_{\Omega^-} < m_{\Omega^- e^+} < m_{\Omega_c^0}$. We require $|\vec{p}_{\Omega^-} + \vec{p}_{e^+}| > 1.4$ GeV/c to reduce background from $B\overline{B}$ events. Figure 2 shows the invariant mass distributions of $\Lambda^0 K^-$ pairs in events which contain a right sign (RS) or wrong sign (WS) positron. 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 a MC simulation to represent the signal and a first order polynomial function to represent the background. We define the signal box as a $\pm 3.0\sigma$ signal region around the Ω^- mass. The fit returns 13.0 ± 3.8 (1.3 ± 0.6) events in the Gaussian component (background component) within the signal box.

We now consider backgrounds to the signal. There are four types of background that produce events that populate the signal box. These are: (1) fake e^+ – real Ω^- combinations, (2) random $\Omega^- e^+$ pairs from (a) the continuum (generic $e^+e^- \to q\overline{q}$ events) where the Ω^- is not a decay product of a charm baryon semileptonic decay and (b) B decays at the $\Upsilon(4S)$, (3) feeddown from decays of the type $\Omega_c^0 \to \Omega^- X e^+ \nu_e$, where X is an unobserved decay product, (4) feedthrough from Ξ_c and Λ_c semileptonic decays. In addition for each of (1), (2), (3), and (4) there is combinatorial background to the Ω^- (usually a Λ^0 with random kaon). This fake Ω^- background is uniformly distrubuted in the $\Lambda^0 K^-$ invariant mass and populates both the signal box and the region outside the signal box. Therefore the population of events outside the signal box can be used to check etimates of the number of background events in the signal box. A further check is provided by wrong sign events which are produced by (1) and (2).

The evaluation of the backgrounds is as follows. The fake positron contribution to both RS and WS events depends on the particle populations in $c\overline{c}$ jets containing an Ω^-, and the species and momentum-dependent fake rate [16]. In this analysis, strangeness (baryon number) conservation leads to enhanced kaon (antiproton) production in $e^+e^- \to \Omega^- X$ events. Both antiprotons and kaons have larger positron fake rates than pions. Because of baryon conservation, fake leptons from baryons are much more numerous in WS than in RS combinations. To account for the different positron fake rates of each particle species, all tracks in events containing an Ω^- that are not positively identified as positrons, are weighted by the momentum-dependent positron 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 positrons in the signal box. Thus, the total contribution from this source is 1.6 ± 0.5 RS events.

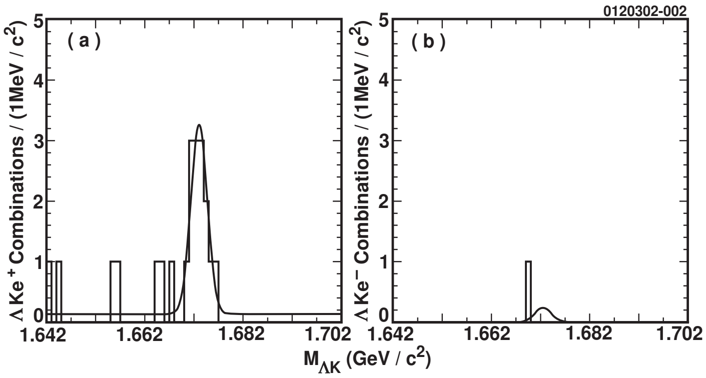

FIG. 2. The invariant mass of $\Lambda^0 K^-$ pairs for events with a positron (right plot) and an electron (left plot) satisfying the selection criteria described in the text.

The Ω^- production mechanisms in continuum events and $\Upsilon(4S) \to B\bar{B}$ decays are not well known, therefore a 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 [8–10]. In this analysis the absence of WS events at the Ω^- mass demonstrates that the random pairing of an Ω^- and a electron is negligible. We assume that this is also true for RS combinations.

Background due to decays of the type $\Omega_c^0 \to \Omega^- e^+ \nu_e X$, 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] which 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 positron 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 this analysis is insensitive to $\Omega_c^0 \to \Omega^- e^+ \nu_e X$.

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 $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$, [8] found that $B(\Lambda_c^+ \to \Lambda^0 e^+ \nu_e)/B(\Lambda_c^+ \to \Lambda^0 e^+ \nu_e X) > 0.85$ at 90 % confidence level. The same pattern is seen in charm mesons [18]. In B meson semileptonic decays where the energy release is larger there is only modest non-resonant 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 anti-quark 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 $\Omega_c^0 \to \Omega^- e^+ \nu_e$, the reconstruction efficiency is an order of magnitude lower, and $M_{\Omega^- e^+} < 1.98$ GeV/c^2 is satisfied. Figure 3 shows the $\Omega^- e^+$ invariant mass distribution for events in the signal box and compares it to the distribution expected for $\Omega_c^0 \to \Omega^- e^+ \nu_e$. The data is consistent with the simulation. There is one event with $M_{\Omega^- e^+} < 1.98$ GeV/c^2 consistent with $\Xi_c \to \Omega^- K e^+ \nu_e$. As this event could be either signal or background, it contributes a 0^{+1}_{-0} event uncertainty to the number of signal events.

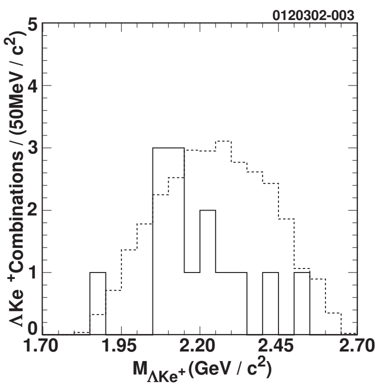

FIG. 3. $\Omega^- e^+$ invariant mass distribution for events in the signal box (solid line) and a Monte Carlo simulation (dashed line).

Feedthrough from other charm baryon semileptonic decays, $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$, $\Xi_c^0 \to \Xi^- e^+ \nu_e$, and $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ (coherent background), is a source of Λ^0 e^+ pairs, which, when combined with a random track in the event satisfying the kaon hypothesis, can mimic the signal. Coherent background is evaluated by generating MC events according to a HQET consistent model [17] which was shown in [10] to describe the decay $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$. The MC events are generated using the measured fragmentation functions of the Λ_c^+, Ξ_c^+, and Ξ_c^0. Since the e^+e^- cross section for each process has been measured [8–10], a reliable prediction of the coherent background can be made. We estimate that the coherent background contributes 3.5 ± 1.9 RS events distributed uniformly in the range $1.642 < m_{\Lambda^0 K^-} < 1.072$ GeV/c^2. Note that the coherent background, and any other source of fake Ω^- – real or fake e^+ is automatically taken into account by fitting the $\Lambda^0 K^-$ mass to determine the yield.

We now compare our estimate of the RS and WS backgrounds to the data. We estimate that fake positron background contributes 0.3 ± 0.3 (0.4 ± 0.4) WS events in the signal box (outside the signal box). The sum is in good agreement with the one WS event observed. We estimate coherent background (fake positron - fake Ω) contribute 2.9 ± 1.6 (1.6 ± 0.5) RS events outside the signal box in reasonable agreement with the the 7 RS events observed outside the signal box. The slight excess observed in data may be attributed to additional sources of fake Ω – real e^+ pairs which have not been accounted for. For example, the assumption that random pairs populate RS and WS equally may not be exact. However, we remind the reader that, due to the fit, the excess is accounted for in the determination of the yield. Finally, we estimate that the coherent background contributes 0.6 ± 0.3 events in the signal box in good agreement with the 1.3 ± 0.6 background events in the signal box returned from the fit.

To estimate the number of signal events in the signal box we subtract the fake positron background from the Gaussian component of the fit to obtain 11.4 ± 3.8 events consistent with $\Omega_c^0 \to \Omega^- e^+ \nu_e$. The probability for the background in the signal box (*i.e.* the sum of the coherent background and the fake positron 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 $B(\Omega_c^0 \to \Omega^- e^+ \nu_e) \cdot \sigma(e^+e^- \to \Omega_c^0 X)$ is $(42.2 \pm 14.1 \pm 5.7)$ fb.

We have considered the following sources of systematic uncertainty and give our estimate of their magnitude in parentheses. Background from the process $\Xi_c \to \Omega^- K e^+ \nu_e$ is estimated from the $\Omega^- e^+$ invariant mass distribution of Figure 3 (7.1%). The uncertainty in the fake positron 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 positron track is determined by our knowledge of the the track finding efficiency of the CLEO II/II.V detectors (1.0%). The uncertainty associated with the positron 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 uncertainties associated with MC modeling of slow pions from Λ^0 decays is obtained by varying this 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 $B(\Omega^- \to \Lambda^0 K^-)$ and $B(\Lambda^0 \to p^+ \pi^-)$ 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 exception is the uncertainties associated with $\Xi_c \to \Omega^- K e^+ \nu_e$ and fake positron background. We assume the event satisfying $M_{\Omega^- e^+} < 1.98$ 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 positron background. The probability for the background to fluctuate to 14 or more events in the 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 [19]. We find 14.1 ± 4.3 events consistent with the decay $\Omega_c^0 \to \Omega^- \pi^+$ [20]. After correcting the yields by the efficiencies we compute $R = \Gamma(\Omega_c^0 \to \Omega^- \pi^+)/\Gamma(\Omega_c^0 \to \Omega^- e^+ \nu_e) = 0.41 \pm 0.19(\text{stat}) \pm 0.04(\text{syst})$. 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 $0.44 \pm 0.09(\text{stat})$ ($0.3 \pm$

0.1(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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[17] J.G. Koerner and M. Kraemer, Phys. Lett. B **275**, 495 (1992). This model describes $\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$. We use the measured value of the form factors found in [10]. Application of this model to $\Xi_c^0 \to \Xi^- e^+ \nu_e$ and $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ is achieved by substitution of the particle masses and the decay asymmetry parameter.

[18] CLEO Collaboration, A. Bean *et al.*, Phys. Lett. **B 317**, 647 (1993) gives $\Gamma(D \to (K + K^*) l \nu_e)/\Gamma(D \to lX) = 0.89 \pm 0.12$.

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

[20] The $\Omega_c^0 \to \Omega^- \pi^+$ yield in this analysis is consistent with that reported in [11].