

## Observation of the $\Omega_c^0$ Charmed Baryon at CLEO

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(Received 11 October 2000)

The CLEO experiment at the CESR collider has used  $13.7 \text{ fb}^{-1}$  of data to search for the production of the  $\Omega_c^0$  (css ground state) in  $e^+e^-$  collisions at  $\sqrt{s} \approx 10.6 \text{ GeV}$ . The modes used to study the  $\Omega_c^0$  are  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Xi^- K^- \pi^+ \pi^+$ ,  $\Xi^0 K^- \pi^+$ , and  $\Omega^- \pi^+ \pi^+ \pi^-$ . We observe a signal of  $40.4 \pm 9.0(\text{stat})$  events at a mass of  $2694.6 \pm 2.6(\text{stat}) \pm 1.9(\text{syst}) \text{ MeV}/c^2$ , for all modes combined.

DOI: 10.1103/PhysRevLett.86.3730

PACS numbers: 14.20.Lq, 13.30.Eg

The  $\Omega_c^0$  ( $c\{ss\}$ ) is a  $J^P = \frac{1}{2}^+$  ground state baryon, where  $\{ss\}$  denotes the symmetric nature of its wave function with respect to the interchange of light-quark spins. The other  $J^P = \frac{1}{2}^+$  and  $J^P = \frac{3}{2}^+$  charmed baryons are well established and their masses have been determined with precision. The  $\Omega_c^0$  is less well established. In this Letter, we report the observation of the  $\Omega_c^0$  in  $e^+e^-$  collisions and a mass measurement of comparable precision to fixed target experiments. Precise mass determination of charmed baryons and comparison with expectations of theoretical models improve our understanding of the strong interaction. Various theoretical models [1–5] predict an  $\Omega_c^0$  mass in the range 2664–2786  $\text{MeV}/c^2$ , but without clear consensus. Differences among previous experiments as well as among theoretical predictions have made it clear that new measurements are needed to better determine the  $\Omega_c^0$  mass.

Many experimental groups have searched for the  $\Omega_c^0$  in numerous decay modes: however, their reported  $\Omega_c^0$  masses are only marginally consistent with each other. The WA62 experiment [6] claimed the first evidence of  $\Omega_c^0$  in the  $\Xi^- K^- \pi^+ \pi^+$  decay mode with a mass of  $2740.0 \pm 20.0 \text{ MeV}/c^2$ . The ARGUS Collaboration [7] published an  $\Omega_c^0$  signal in the  $\Xi^- K^- \pi^+ \pi^+$  mode with a mass of  $2719.0 \pm 7.0 \pm 2.5 \text{ MeV}/c^2$ , based on  $0.380 \text{ fb}^{-1}$  of data. This result was contradicted by CLEO, in an unpublished conference paper [8], using  $1.8 \text{ fb}^{-1}$  of data. Later, E687 published an  $\Omega_c^0$  mass of  $2705.9 \pm 3.3 \pm 2.3 \text{ MeV}/c^2$  using the  $\Omega^- \pi^+$  mode [9] and a mass of  $2699.9 \pm 1.5 \pm 2.5 \text{ MeV}/c^2$  using the higher-statistics  $\Sigma^+ K^- K^- \pi^+$  mode [10]. In 1995, the WA89 Collaboration [11] reported 200  $\Omega_c^0$  events in seven decay modes with an average mass of  $2707.0 \pm 1.0(\text{stat}) \text{ MeV}/c^2$ ; this result remains unpublished.

The data used in this analysis were collected with CLEO II [12] and the upgraded CLEO II.V [13] detector operating at the Cornell Electron Storage Ring (CESR). The data correspond to an integrated luminosity of  $13.7 \text{ fb}^{-1}$  from the  $Y(4S)$  resonance and at energies in the continuum region just below. We searched for the  $\Omega_c^0$  in the five decay modes  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Omega^- \pi^+ \pi^+ \pi^-$ ,  $\Xi^- K^- \pi^+ \pi^+$ , and  $\Xi^0 K^- \pi^+$ . The choice of these five modes is based mainly on the pattern of other charmed baryon decays. Reconstruction efficiencies and the size of the combinatorial background were other considerations. A sixth channel,  $\Sigma^+ K^- K^- \pi^+$ , was also investigated because E687 [10] showed a significant signal in this decay mode, although CLEO has rather low efficiency for this mode.

Charmed baryons at CESR are produced either from the secondary decays of  $B$  mesons or directly from  $e^+e^-$  annihilations to  $c\bar{c}$  jets. We introduce  $x_p$  as the scaled momentum of a  $\Omega_c^0$  candidate, where  $x_p = p/p_{\text{max}}$ , and  $p_{\text{max}} = \sqrt{E_b^2 - M^2}$  with  $E_b$  equal to the beam energy and  $M$  the mass of the  $\Omega_c^0$  candidate. Our search is limited to  $x_p > 0.5$  or  $x_p > 0.6$ , depending on the decay mode, so as to avoid the combinatorial background that dominates at low  $x_p$ . Charmed baryons from  $B$  meson decays are kinematically limited to  $x_p < 0.4$ , so our search is limited to the  $\Omega_c^0$  baryons produced in the  $e^+e^-$  continuum. We implemented  $p/K/\pi$  identification by defining a joint probability for each hypothesis, using both the specific ionization ( $dE/dx$ ) in the drift chamber and the time-of-flight to the scintillation counters. A charged track is defined to be consistent with a particular particle hypothesis if the corresponding probability is greater than 0.1%. We required all the charge tracks in all the decay modes to be consistent with their respective particle hypotheses. To further reduce the combinatorial background we also required the momentum of daughter pions and kaons from  $\Omega_c^0$  to be greater than 0.2 to 0.5  $\text{GeV}/c$  depending on the decay mode.

We begin the analysis by reconstructing  $\Lambda \rightarrow p\pi^-$ ,  $\Xi^0 \rightarrow \Lambda\pi^0$ ,  $\Xi^- \rightarrow \Lambda\pi^-$ ,  $\Omega^- \rightarrow \Lambda K^-$ , and  $\Sigma^+ \rightarrow p\pi^0$ . Charge conjugation is implied throughout the analysis. The analysis procedure for reconstructing these particles closely follows that presented elsewhere [14–16]. The hyperons are required to have vertices well separated from the beam spot, with the flight distance of the secondary  $\Lambda$  greater than that of the  $\Xi^0$ ,  $\Xi^-$ , or  $\Omega^-$ . We then combine these hyperons with tracks from the primary event vertex to reconstruct  $\Omega_c^0$  candidates.

In each mode the signal area above the background is obtained by fitting with the sum of a Gaussian signal function (with width fixed at the signal Monte Carlo predicted value for that mode) and a second order polynomial background. The Monte Carlo sample used in this analysis was generated for the two CLEO detector configurations using a GEANT-based [17] simulation and was processed similarly to the data. We simultaneously fit the five modes to a single mean value for the mass. In the  $\Omega^- \pi^+$  mode, we required  $x_p$  to be greater than 0.5 and the  $\pi^+$  momentum to be greater than 0.5  $\text{GeV}/c$ . Figure 1(a) shows the invariant mass distribution; a fit to this distribution yields a signal of  $13.3 \pm 4.1$  events. In the  $\Omega^- \pi^+ \pi^0$  mode, only  $\gamma\gamma$  combinations having invariant mass within 12.5  $\text{MeV}/c^2$  (2.5 standard deviation) of the nominal  $\pi^0$  mass are used as  $\pi^0$  candidates; we assume the photons

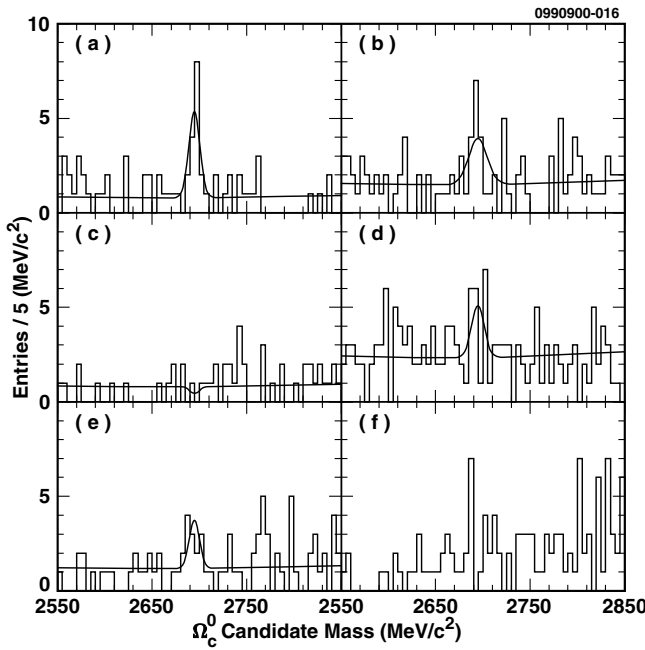


FIG. 1. The mass distribution and simultaneous fit to the five  $\Omega_c^0$  modes: (a)  $\Omega^- \pi^+$ , (b)  $\Omega^- \pi^+ \pi^0$ , (c)  $\Omega^- \pi^+ \pi^- \pi^+$ , (d)  $\Xi^0 K^- \pi^+$ , (e)  $\Xi^- K^- \pi^+ \pi^+$ . The mode (f)  $\Sigma^+ K^- K^- \pi^+$  has not been included in the fit. The signal is fit with a Gaussian of fixed width while the background is fit to a second order polynomial.

used for reconstructing  $\pi^0 \rightarrow \gamma\gamma$  come from the event vertex. We also required  $x_p$  to be greater than 0.5 and the  $\pi^+$  and  $\pi^0$  momenta to be greater than 0.3 and 0.5 GeV/c, respectively. Figure 1(b) shows the invariant mass distribution. A fit to the distribution gives a signal yield of  $11.8 \pm 4.9$  events. Figure 1(c) shows the  $\Omega^- \pi^+ \pi^- \pi^+$  invariant mass distribution for  $x_p$  greater than 0.5. All

the charged pions are required to have momenta greater than 0.2 GeV/c. The corresponding fit yields a signal of  $-0.9 \pm 1.4$  events. In the  $\Xi^0 K^- \pi^+$  mode, we considered combinations with  $x_p$  greater than 0.6, since the combinatorial background is higher in this mode. Figure 1(d) shows the invariant mass distribution, with a fit yielding a signal of  $9.2 \pm 4.9$  events. In the  $\Xi^- K^- \pi^+ \pi^+$  mode, we required  $x_p$  to be greater than 0.6 and pion and kaon momenta to be greater than 0.2 and 0.3 GeV/c, respectively. A fit to this distribution yields a signal of  $7.0 \pm 3.7$  events. Finally, in the  $\Sigma^+ K^- K^- \pi^+$  mode, we required  $x_p$  to be greater than 0.5 and required charged track momenta to be greater than 0.3 GeV/c. The upper limit on the yield is 9.5 events (90% C.L.). Figure 1(f) shows the invariant mass distribution for  $\Sigma^+ K^- K^- \pi^+$  mode. The efficiency for  $\Sigma^+ K^- K^- \pi^+$  reconstruction is  $\sim 15\%$  of that for the  $\Omega^- \pi^+$  mode, which has the highest signal yield. We have not included the  $\Sigma^+ K^- K^- \pi^+$  mode in the mass measurement. The total yield in the five decay modes, excluding  $\Sigma^+ K^- K^- \pi^+$ , is  $40.4 \pm 9.0$  events as shown in Table I. The corresponding combined mass distribution is shown in Fig. 2.

To better determine the  $\Omega_c^0$  mass, we have performed an unbinned maximum-likelihood fit using the sum of a single Gaussian and a second order polynomial background. There are two inputs to the fit, the invariant mass  $M_i$  and the corresponding mass resolution  $\sigma_i$  of each of the 458 mass candidates from 2.55 to 2.85 GeV/c<sup>2</sup>. The invariant mass  $M_i$  of each candidate is calculated using a vertex constrained fit; the uncertainty  $\sigma_i$  is obtained from the covariance matrix of the fit. The likelihood function to maximize is the product of probability density functions (PDFs) for all the candidate events, and has the following form:

$$\mathcal{L}(M(\Omega_c^0), f_s, a_1, a_2) = \prod_i \left[ f_s G(M_i - M(\Omega_c^0) | S\sigma_i) + (1 - f_s) \frac{P(M_i)}{\int_{2.55}^{2.85} P(M_i) dM_i} \right], \quad (1)$$

where  $G(y | \sigma) = (1/\sqrt{2\pi\sigma}) \exp(-y^2/2\sigma^2)$  and  $P(y) = 1.0 + a_1(y - 2.7) + a_2(y - 2.7)^2$ .  $M(\Omega_c^0)$  is the fitted  $\Omega_c^0$  mass,  $S$  is a global scale factor multiplying  $\sigma_i$ , and  $f_s$  is the fraction of signal events. We tested the fitting procedure by first applying it to Monte Carlo generated

events with the  $\Omega_c^0$  mass set to 2695 MeV/c<sup>2</sup>. The fitted mass using the above PDF is  $2694.9 \pm 0.1(\text{stat})$  MeV/c<sup>2</sup> for the Monte Carlo and  $2694.6 \pm 2.6(\text{stat})$  MeV/c<sup>2</sup> for the data. The fitted scale factor  $S$  is  $1.72 \pm 0.42$  for the

TABLE I.  $\Omega_c^0$  results in different decay modes. The fourth column shows the branching fractions relative to  $\Omega^- \pi^+$ ; the fifth column shows the cross section times branching fraction. The third column has only statistical uncertainty, while the fourth and fifth columns have statistical and systematic uncertainties.

	$\sigma_{MC}(\text{MeV}/c^2)$	Fitted yield mode dependent $x_p$	Relative $\mathcal{B}$ all $x_p > 0.5$	$\sigma \cdot \mathcal{B}$ (fb) all $x_p > 0.5$
$\Omega^- \pi^+$	5.87	$13.3 \pm 4.1$	1	$11.3 \pm 3.9 \pm 2.0$
$\Omega^- \pi^+ \pi^0$	9.71	$11.8 \pm 4.9$	$4.2 \pm 2.2 \pm 0.9$	$47.6 \pm 18.0 \pm 3.1$
$\Xi^0 K^- \pi^+$	6.72	$9.2 \pm 4.9$	$4.0 \pm 2.5 \pm 0.4$	$45.1 \pm 23.2 \pm 3.7$
$\Xi^- K^- \pi^+ \pi^+$	5.46	$7.0 \pm 3.7$	$1.6 \pm 1.1 \pm 0.4$	$18.2 \pm 10.6 \pm 3.3$
$\Omega^- \pi^+ \pi^- \pi^+$	4.89	$-0.9 \pm 1.4$	$<0.56$	$<5.1$ @ 90% C.L.
Combined 5 modes		$40.4 \pm 9.0$		
$\Sigma^+ K^- K^- \pi^+$	6.18	$2.8 \pm 4.1$	$<4.8$	$<53.8$ @ 90% C.L.

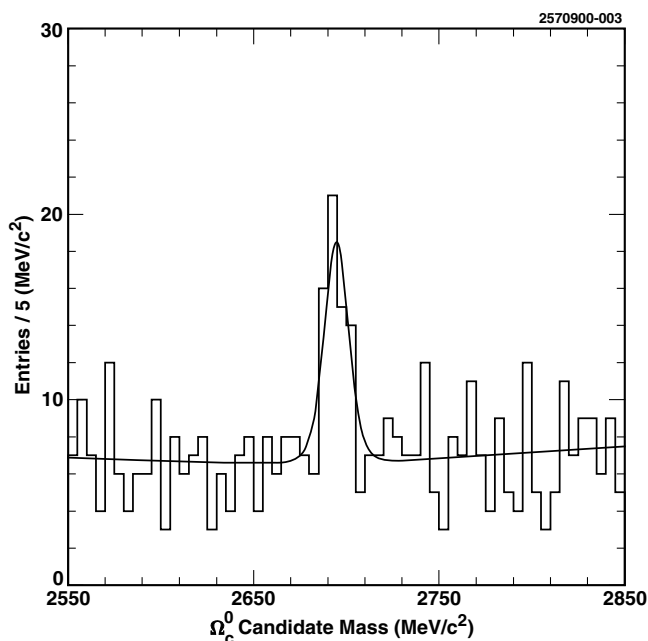


FIG. 2. The invariant mass distribution for the sum of  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Omega^- \pi^+ \pi^+ \pi^-$ ,  $\Xi^0 K^- \pi^+$ , and  $\Xi^- K^- \pi^+ \pi^+$  combinations. The fit function is a sum of the fit functions from Fig. 1.

data and  $1.16 \pm 0.02$  for the simulated events. The fitted value of  $f_s = 0.099 \pm 0.027(\text{stat})$  implies a signal size of  $45.2 \pm 13.7(\text{stat})$  in good agreement with the result from Table I. We tested our fitter on the  $\Xi_c^0$  charmed baryon in the  $\Xi^- \pi^+$  final state. Our fit gives a  $\Xi_c^0$  mass that is consistent with the world average value, and the fitted global scale factor  $S$  for the  $\Xi_c^0$  Monte Carlo and the data are in good agreement with each other.

We have also checked for goodness-of-fit by performing a binned-likelihood version of the above fit (but without event-by-event mass uncertainties). This gives an almost identical mass value and similar yields, and forms the basis for the curve shown in Fig. 2. The  $\chi^2$  for the fit to the combined data is 46.2 for 46 degrees of freedom.

The dominant systematic uncertainty in the mass measurement comes from its sensitivity to the fitting method employed—the difference in the weighted average of the individually fitted  $\Omega_c^0$  modes and the unbinned maximum likelihood method. The various fitting methods contribute  $1.5 \text{ MeV}/c^2$  to the systematic uncertainty. A systematic uncertainty ( $0.5 \text{ MeV}/c^2$ ) comes from imperfect treatment of modes with  $\pi^0$  mesons due to mismeasured photons at low energies that give rise to an asymmetric  $\pi^0$  peak. Additional contributions to the systematic uncertainty come from uncertainties in the energy loss correction for charged tracks ( $0.25 \text{ MeV}/c^2$ ) and the overall momentum scale ( $1.0 \text{ MeV}/c^2$ ). Taking these errors in quadrature, we estimate a total systematic uncertainty of  $1.9 \text{ MeV}/c^2$ .

In Table I we also give the measured inclusive cross section times the branching fraction,  $\sigma \cdot \mathcal{B}$ , for  $x_p > 0.5$  into  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Xi^- K^- \pi^+ \pi^+$ ,  $\Xi^0 K^- \pi^+$ ,  $\Omega^- \pi^+ \pi^+ \pi^-$ , and  $\Sigma^+ K^- K^- \pi^+$ . We estimated the sys-

tematic errors for the branching fractions by changing the  $\Omega_c^0$  mass by  $\pm 1.0\sigma$  (combined error) from its best fit value. In Table I the first error is due to statistics and the second, when given, to systematics. The E687 [10] experiment has also measured upper limits for the relative branching fractions  $\mathcal{B}(\Xi^- K^- \pi^+ \pi^+)/\mathcal{B}(\Omega^- \pi^+) < 2.8$  and  $\mathcal{B}(\Omega^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(\Omega^- \pi^+) < 1.6$  at 90% C.L.; these are consistent with our measurements given in Table I. In charm decays,  $c \rightarrow Ws$ , the  $W$  tends to couple more strongly to two pions (via the  $\rho$  meson) than to a single pion. The relative branching fraction  $\mathcal{B}(c \rightarrow s \pi^+ \pi^0)/\mathcal{B}(c \rightarrow s \pi^+)$  is greater than unity. The relative branching fractions for  $\mathcal{B}(D^+ \rightarrow \bar{K}^0 \pi^+ \pi^0)/\mathcal{B}(D^+ \rightarrow \bar{K}^0 \pi^+)$ ,  $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^0)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ , and  $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0)/\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \pi^+)$  are  $3.4 \pm 1.1(\text{stat})$ ,  $3.6 \pm 0.2(\text{stat})$ , and  $4.0 \pm 1.9(\text{stat})$  [18], respectively. We also observe a similar trend in the branching fraction for  $\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^0$  relative to  $\Omega_c^0 \rightarrow \Omega^- \pi^+$ , as given in Table I. We have also studied the momentum spectrum of  $\Omega_c^0$ , finding it consistent with other charmed baryons [19].

In conclusion, using the sum of five decay modes  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Omega^- \pi^+ \pi^+ \pi^-$ ,  $\Xi^- K^- \pi^+ \pi^+$ , we observe a clear signal for  $\Omega_c^0$  production with a signal yield of  $40.4 \pm 9.0(\text{stat})$  events and a mass of  $2694.6 \pm 2.6(\text{stat}) \pm 1.9(\text{syst}) \text{ MeV}/c^2$ . We report on measurements of  $\sigma \cdot \mathcal{B}$  in the  $\Omega^- \pi^+$ ,  $\Omega^- \pi^+ \pi^0$ ,  $\Omega^- \pi^+ \pi^+ \pi^-$ ,  $\Xi^- K^- \pi^+ \pi^+$  and give upper limits for  $\Omega^- \pi^+ \pi^+ \pi^-$  and  $\Sigma^+ K^- K^- \pi^+$  modes at the 90% C.L., as mentioned in Table I. Although the signal is not statistically significant in any individual mode, the combined signal stands out over the background. Our measured  $\sigma \cdot \mathcal{B}$  value for the  $\Xi^- K^- \pi^+ \pi^+$  mode ( $18.2 \pm 10.6 \pm 3.3 \text{ fb}$ ) is in clear disagreement with the ARGUS value ( $2410 \pm 900 \pm 300 \text{ fb}$ ) for the same  $x_p$  range.

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, the U.S. Department of Energy, the Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A.P. Sloan Foundation, the Swiss National Science Foundation, the Texas Advanced Research Program, and the Alexander von Humboldt Stiftung.

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