CLNS 00-1695
CLEO 00-19

Observation of the Ω_c^0 Charmed Baryon at CLEO

CLEO Collaboration

(October 17, 2000)

Abstract

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

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Many experimental groups have searched for the Ω_c^0 in numerous decay modes: however, their reported Ω_c^0 masses are only marginally consistent with each other. The WA62 experiment [1] claimed the first evidence of Ω_c^0 in the $\Xi^- K^- \pi^+ \pi^+$ decay mode with a mass of 2740.0 ± 20.0 MeV/c^2. The ARGUS Collaboration [2] published an Ω_c^0 signal in the $\Xi^- K^- \pi^+ \pi^+$ mode with a mass of $2719.0 \pm 7.0 \pm 2.5$ MeV/c^2, based on 0.380 fb^{-1} of data. This result was contradicted by CLEO, in an unpublished conference paper [3] using 1.8 fb^{-1} of data. Later, E687 [4] published an Ω_c^0 mass of $2705.9 \pm 3.3 \pm 2.3$ MeV/c^2 using the $\Omega^- \pi^+$ mode and a mass of $2699.9 \pm 1.5 \pm 2.5$ MeV/c^2 using the higher-statistics $\Sigma^+ K^- K^- \pi^+$ mode. In 1995, the WA89 Collaboration [5] reported 200 Ω_c^0 events in seven decay modes with an average mass of 2707.0 ± 1.0(stat) MeV/c^2; this result remains unpublished.

The Ω_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. Various theoretical models [6–9] predict an Ω_c^0 mass in the range 2664 - 2786 MeV/c^2.

The data used in this analysis were collected with CLEO II [10] and the upgraded CLEO II.V [11] detector operating at the Cornell Electron Storage Ring (CESR). The data corresponds to an integrated luminosity of 13.7 fb^{-1} from the $\Upsilon(4S)$ resonance and at energies in the continuum region just below. We searched for the Ω_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 [4] showed a significant signal in this decay mode, although CLEO has rather low efficiency for this mode.

Charmed baryons at CESR are either produced 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 Ω_c^0 candidate, where $x_p = p/p_{\max}$, and $p_{\max} = \sqrt{E_{\rm b}^2 - M^2}$ with $E_{\rm b}$ equal to the beam energy and M the mass of the Ω_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 Ω_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 Ω_c^0 to be greater than 0.2 GeV/c to 0.5 GeV/c depending on the decay mode.

We begin the analysis by reconstructing $\Lambda \to p\pi^-$, $\Xi^0 \to \Lambda\pi^0$, $\Xi^- \to \Lambda\pi^-$, $\Omega^- \to \Lambda K^-$, and $\Sigma^+ \to p\pi^0$. Charge conjugation is implied throughout the analysis. The analysis procedure for reconstructing these particles closely follows that presented elsewhere [12–14]. The hyperons are required to have vertices well separated from the beamspot, with the flight distance of the secondary Λ greater than that of the Ξ^0, Ξ^-, or Ω^-. We then combine these hyperons with tracks from the primary event vertex to reconstruct Ω_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 [15] 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 π^+ momentum to be greater than 0.5 GeV/c. Figure 1(a) shows the invariant mass distribution; a fit to this distribution yields a signal of 13.3 ± 4.1 events. In the $\Omega^-\pi^+\pi^0$ mode, only $\gamma\gamma$ combinations having invariant mass within 12.5 MeV/c^2(2.5 standard deviation) of the nominal π^0 mass are used as π^0 candidates; we assume the photons used for reconstructing $\pi^0 \to \gamma\gamma$ come from the event vertex. We also required x_p to be greater than 0.5 and the π^+ and π^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 ± 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 ± 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 ± 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 ± 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 decays modes, excluding $\Sigma^+ K^- K^- \pi^+$, is 40.4 ± 9.0 events as shown in Table I. The corresponding combined mass distribution is shown in Figure 2.

To better determine the Ω_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 σ_i of each of the 458 mass candidates from 2.55 to 2.85 GeV/c^2. The invariant mass M_i of each candidate is calculated using a vertex constrained fit; the uncertainty σ_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:

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

where $\mathrm{G}(y|\sigma) = (1/\sqrt{2\pi\sigma})\exp(-y^2/2\sigma^2)$ and $\mathrm{P}(y) = 1.0 + a_1(y - 2.7) + a_2(y - 2.7)^2$. $M(\Omega_c^0)$ is the fitted Ω_c^0 mass, S is a global scale factor multiplying σ_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 Ω_c^0 mass set to 2695 MeV/c^2. The fitted mass using the above PDF is 2694.9±0.1(stat) MeV/c^2 for the Monte Carlo and 2694.6±2.6(stat) MeV/c^2 for the data. The fitted scale factor S is 1.72±0.42 for the data and 1.16±0.02 for the simulated events. The fitted value of $f_s = 0.099 \pm 0.027$(stat) implies a signal size of 45.2±13.7(stat) in good agreement with the result from Table I. We tested our fitter on the Ξ_c^0 charmed baryon in the $\Xi^-\pi^+$ final state. Our fit gives a Ξ_c^0 mass that is consistent with the world average value, and the fitted global scale factor S for the Ξ_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 Figure 2. The χ^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 Ω_c^0 modes and the unbinned maximum likelihood method. The various fitting methods contribute 1.5 MeV/c^2 to the systematic uncertainty. A systematic uncertainty (0.5 MeV/c^2) comes from imperfect treatment of modes with π^0 mesons due to mismeasured photons at low energies that give rise to an asymmetric π^0 peak. Additional contributions to the systematic uncertainty come from uncertainties in the energy loss correction for charged tracks (0.25 MeV/c^2) and the overall momentum scale (1.0 MeV/c^2). Taking these errors in quadrature, we estimate a total systematic uncertainty of 1.9 MeV/c^2.

In Table I we also give the measured inclusive cross-section times the branching faction, $\sigma \cdot \mathcal{B}$, for $x_p > 0.5$ into $\Omega^-\pi^+$, $\Omega^-\pi^+\pi^0$, $\Xi^-K^-\pi^+\pi^+$, $\Xi^0K^-\pi^+$, $\Omega^-\pi^+\pi^+\pi^-$and $\Sigma^+K^-K^-\pi^+$. We estimated the systematic errors for the branching fractions by changing the Ω_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. In charm decays, $c \to Ws$, the W tends to couple more strongly to two pions (via the ρ-meson) than to a single pion. The relative branching fraction $\mathcal{B}(c \to s\pi^+\pi^0)/\mathcal{B}(c \to s\pi^+)$ is greater than unity. The relative branching fractions for $\mathcal{B}(D^+ \to \overline{K^0}\pi^+\pi^0)/\mathcal{B}(D^+ \to \overline{K^0}\pi^+)$, $\mathcal{B}(D^0 \to K^-\pi^+\pi^0)/\mathcal{B}(D^0 \to K^-\pi^+)$, and $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)/\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)$ are 3.4±1.1(stat), 3.6±0.2(stat), and 4.0±1.9(stat) [16], respectively. We also observe a similar trend in the branching fraction for $\Omega_c^0 \to \Omega^-\pi^+\pi^0$ relative to $\Omega_c^0 \to \Omega^-\pi^+$, as given in Table I. We have also studied the momentum spectrum of Ω_c^0, finding it consistent with other charmed baryons [17].

TABLE I. Ω_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 fourth column has only statistical, while fourth and fifth columns have statistical and systematic uncertainties.

	σ_{MC}(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±4.1	1.0	$11.3 \pm 3.9 \pm 2.0$
$\Omega^-\pi^+\pi^0$	9.71	11.8±4.9	$4.2 \pm 2.2 \pm 0.9$	$47.6 \pm 18.0 \pm 3.1$
$\Xi^0K^-\pi^+$	6.72	9.2±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±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±1.4	< 0.56	< 5.1 @ 90 % CL
Combined 5 modes		40.4±9.0		
$\Sigma^+K^-K^-\pi^+$	6.18	2.8±4.1	< 4.8	< 53.8 @ 90 % CL

In conclusion, we observe the Ω_c^0 with a mass of 2694.6±2.6(stat)±1.9(syst) MeV/c^2 in the five decay modes $\Omega^-\pi^+$, $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^-K^-\pi^+\pi^+$, and $\Xi^0K^-\pi^+$. Although the signal is not statistically significant in any individual mode, the combined signal stands out over the background with a yield of 40.4$\pm$9.0(stat) events. Our measured $\sigma \cdot \mathcal{B}$ value for the $\Xi^-K^-\pi^+\pi^+$ mode ($18.2 \pm 10.6 \pm 3.3$ fb) is in clear disagreement with the ARGUS value ($2410 \pm 900 \pm 300$ 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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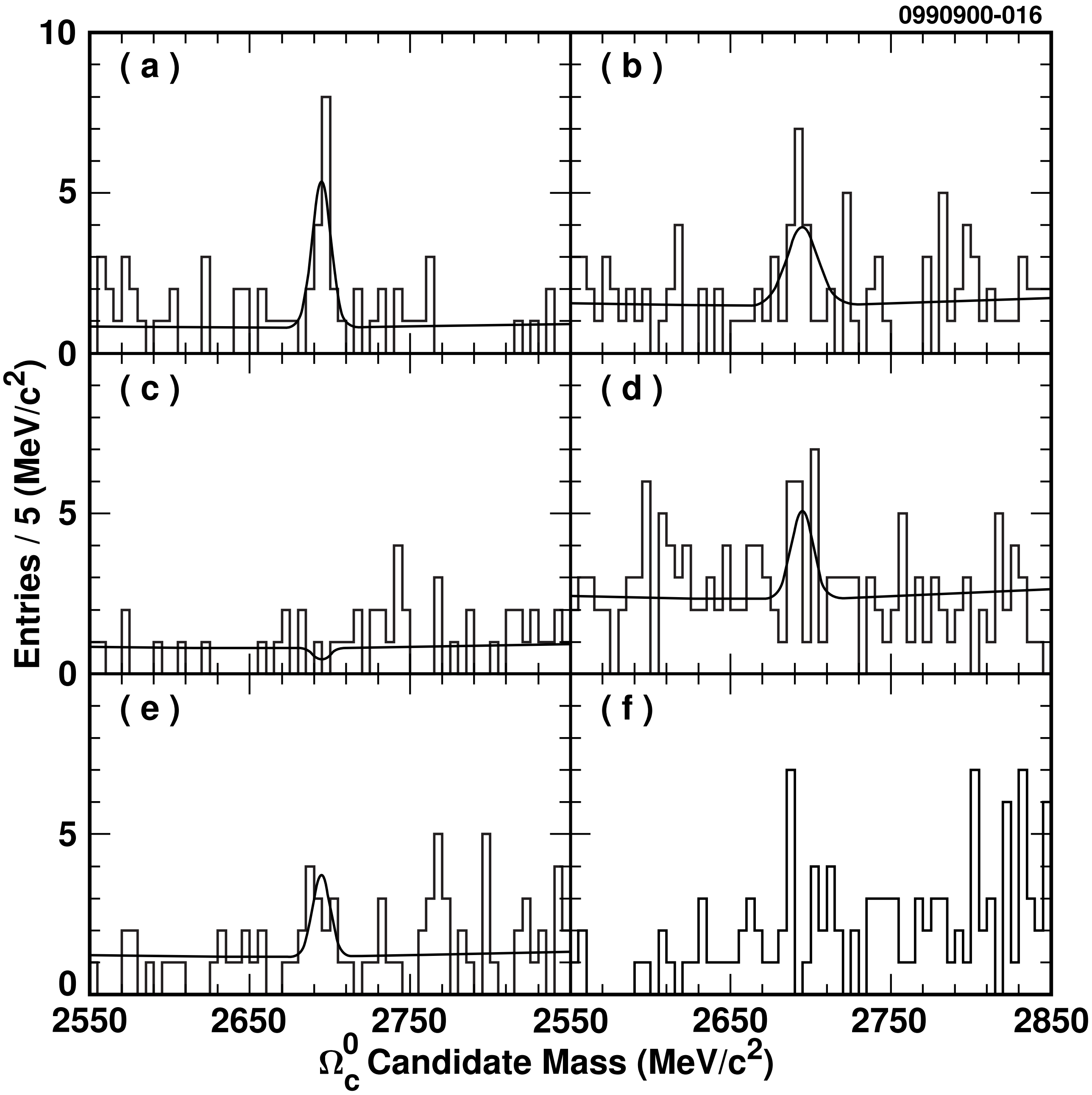

FIG. 1. The mass distribution and simultaneous fit to the five Ω_c^0 modes: (a) $\Omega^-\pi^+$, (b) $\Omega^-\pi^+\pi^0$, (c) $\Omega^-\pi^+\pi^+\pi^-$, (d) $\Xi^0K^-\pi^+$, (e) $\Xi^-K^-\pi^+\pi^+$. The mode (f) $\Sigma^+K^-K^-\pi^+$ has not been included in the fit. The signal is fit with a gaussian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

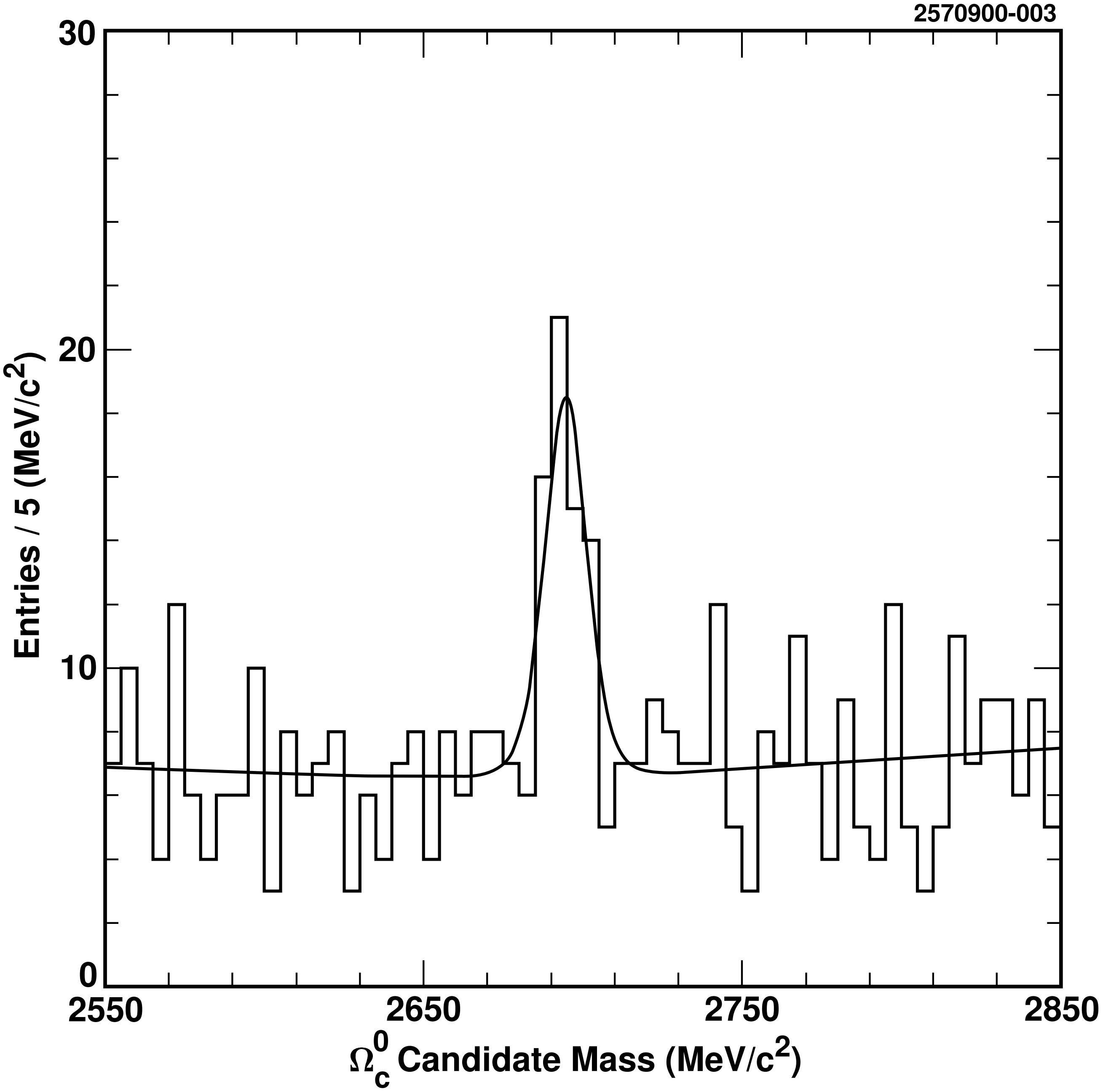

FIG. 2. The invariant mass distribution for the sum of $\Omega^-\pi^+$, $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^0 K^-\pi^+$, and $\Xi^- K^-\pi^+\pi^+$combinations. The fit function is a sum of the fit functions from Figure 1.