

## Observation of a Charmed Baryon Decaying to $D^0 p$ at a Mass Near $2.94 \text{ GeV}/c^2$

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A search for charmed baryons decaying to  $D^0 p$  reveals two states: the  $\Lambda_c(2880)^+$  baryon and a previously unobserved state at a mass of  $[2939.8 \pm 1.3(\text{stat}) \pm 1.0(\text{syst})]$  MeV/ $c^2$  and with an intrinsic width of  $[17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst})]$  MeV. Consistent and significant signals are observed for the  $K^- \pi^+$  and  $K^- \pi^+ \pi^- \pi^+$  decay modes of the  $D^0$  in  $287 \text{ fb}^{-1}$  annihilation data recorded by the *BABAR* detector at a center-of-mass energy of 10.58 GeV. There is no evidence in the  $D^+ p$  spectrum of doubly charged partners. The mass and intrinsic width of the  $\Lambda_c(2880)^+$  baryon and relative yield of the two baryons are also measured.

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Charmed baryons are expected to exhibit a rich spectrum of states. Only a few of these states have been confirmed [1]. The heaviest singly charmed baryon previously observed is the  $\Lambda_c(2880)^+$  decaying to  $\Lambda_c \pi^+ \pi^-$  [2]. The  $\Lambda_c(2880)^+$  baryon is notable not only due to its narrow width ( $< 8$  MeV) but also because it is one of only two singly charmed baryons, along with the  $\Xi_c(2815)$  [3], found above the  $Dp$  mass threshold.

Presented in this Letter is the observation of a new charmed baryon decaying to  $D^0 p$  [4] with a mass of approximately 2.94 GeV/ $c^2$  and an intrinsic width of approximately 20 MeV. This baryon, tentatively labeled the  $\Lambda_c(2940)^+$ , is observed in  $287 \text{ fb}^{-1}$  of  $e^+ e^-$  annihilation data collected near  $\sqrt{s} = 10.58$  GeV by the *BABAR* detector [5] at the PEP-II asymmetric-energy  $e^+ e^-$  storage rings. Along with this new baryon, the decay  $\Lambda_c(2880)^+ \rightarrow D^0 p$  is also observed. The masses, intrinsic widths of both baryons and their relative production rate are measured. The observed mass of the  $\Lambda_c(2940)^+$  is consistent with any of three excited  $\Lambda_c$  baryons of different spin-parity quantum numbers predicted from relativistic quark model calculations [6].

The goal of this analysis is to study the inclusive  $D^0 p$  mass spectrum. Two samples of  $D^0$  mesons are identified using the  $K^- \pi^+$  and  $K^- \pi^+ \pi^- \pi^+$  final states. Each sample is produced by combining charged tracks of the appropriate composition in a geometric fit to a common vertex. The  $\chi^2$  probability of this fit is required to exceed 2%. Charged particle species ( $K^+$ ,  $\pi^+$ ,  $p$ ) are separated using a likelihood algorithm that combines data from a ring-imaging Cherenkov detector with the measured energy loss in the tracking systems [5]. Each proton candidate is combined with each  $D^0$  candidate using a geometric vertex fit that assumes a common production point within the nominal beam envelope. The  $\chi^2$  probability of this fit is required to be better than 2%.

Requirements are imposed on three additional quantities to improve the signal purity of the  $D^0 p$  samples:  $\Delta m$ , the difference between the reconstructed  $D^0$  mass and the accepted value of  $m_{D^0} = 1864.6$  MeV/ $c^2$  [1];  $p^*$ , the  $e^+ e^-$  center-of-mass momentum of the  $D^0 p$  system; and  $\cos \vartheta$ , where  $\vartheta$  is angle of the proton with respect to the  $e^+ e^-$  system in the  $D^0 p$  center-of-mass frame. For isotropic production [expected for the  $\Lambda_c(2940)^+$ ], the  $\cos \vartheta$  distribution will be flat whereas background tends to peak at  $\pm 1$ . Monte Carlo (MC) simulated data samples are

studied in order to determine the specific requirements on these quantities that maximize the expected significance of signals introduced in the mass region near 2940 MeV/ $c^2$ . The resulting best criteria are  $|\Delta m| < 14$  MeV/ $c^2$ ,  $p^* > 2.6$  GeV/ $c$ , and  $\cos \vartheta < 0.8$  for the  $D^0 \rightarrow K^- \pi^+$  sample and  $|\Delta m| < 9$  MeV/ $c^2$ ,  $p^* > 2.8$  GeV/ $c$ , and  $\cos \vartheta < 0.8$  for the  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  sample. The  $\Delta m$  requirements correspond to approximately 2 standard deviations in  $D^0$  mass resolution. The  $p^*$  requirement removes all sources of  $D^0 p$  combinations from  $B$  meson decay.

A MC simulation of a baryon of mass 2.94 GeV/ $c^2$  decaying to  $D^0 p$  predicts selection efficiencies between 30% and 38% for the  $D^0 \rightarrow K^- \pi^+$  final state depending on  $p^*$  and between 12% and 14% for the  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  final state. A proton purity of approximately 83% in the final  $D^0 p$  sample is estimated from studies of a comparable MC sample.

To calculate a  $D^0 p$  invariant mass, each  $D^0$  candidate is assigned an energy that is consistent with a  $D^0$  mass of  $m_{D^0}$ . The resulting combined  $D^0 p$  invariant mass spectrum is shown in Fig. 1. Two peaks are apparent. The clear signal

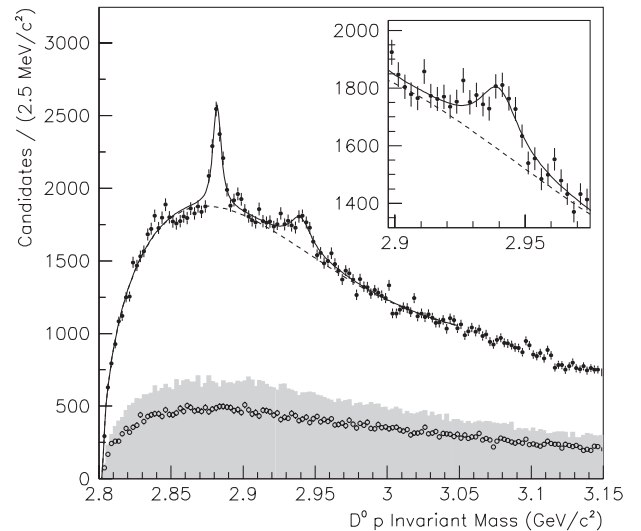


FIG. 1. The solid points are the  $D^0 p$  invariant mass distribution of the final sample. Also shown are (gray) the contribution from false  $D^0$  candidates estimated from  $D^0$  mass sidebands and (open points) the mass distribution from wrong-sign  $\bar{D}^0 p$  candidates. The solid curve is the fit described in the text. The dashed curve is the portion of that fit attributed to combinatorial background.

at  $2.88 \text{ GeV}/c^2$  is likely due to the decay of the  $\Lambda_c(2880)^+$  baryon. The signal at  $2.94 \text{ GeV}/c^2$  is the evidence for the new  $\Lambda_c(2940)^+$  baryon. No similar structures are observed in the wrong-sign  $\bar{D}^0 p$  candidate combinations. Candidates selected from  $D^0$  mass sidebands (of width  $10 \text{ MeV}/c^2$  centered at  $\Delta m = \pm 58 \text{ MeV}/c^2$ ) are used to estimate the contribution from non- $D^0$  sources (see Fig. 1). This sideband sample shows no structure.

An unbinned likelihood fit is used to model the  $D^0 p$  spectrum from the kinematic limit up to  $3.05 \text{ GeV}/c^2$ . This fit includes  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  states, each modeled by a relativistic Breit-Wigner lineshape  $\sigma(m)$  convolved with a Gaussian resolution function. The Breit-Wigner line shape  $\sigma(m)$  is

$$\sigma(m) \propto \frac{q(m)}{(m^2 - m_0^2)^2 + m_0^2 \Gamma^2}, \quad (1)$$

where  $\Gamma$  is the intrinsic width and is constant (i.e., not mass dependent),  $m_0$  is the mass pole, and  $q$  is the three-momentum magnitude of the  $D^0$  or proton in the  $D^0 p$  rest frame for a given mass  $m$ . The detector resolution is obtained from MC simulation which predicts  $1.8 \text{ MeV}/c^2$  and  $1.3 \text{ MeV}/c^2$  for the  $D^0 \rightarrow K^- \pi^+$  and  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  samples, respectively.

The product of a fourth-order polynomial and two-body phase space [1] is used to model the combinatorial background. A fit based on this background shape and the  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  signals is shown in Fig. 1 and results in a  $\Lambda_c(2940)^+$  mass of  $2939.8 \pm 1.3 \text{ MeV}/c^2$ , a width of  $17.5 \pm 5.2 \text{ MeV}$ , and a raw yield of  $2280 \pm 310$  decays (statistical errors only). The  $\Lambda_c(2880)^+$  properties obtained are a mass of  $2881.9 \pm 0.1 \text{ MeV}/c^2$  and a width of  $5.8 \pm 1.5 \text{ MeV}$ , consistent with the CLEO results [2], and a raw yield of  $2800 \pm 190$  decays (statistical errors only). If the  $\Lambda_c(2940)^+$  signal is removed from the fit, the log likelihood changes by 38.2, which is equivalent (in 1 degree of freedom) to a signal significance of 8.7 standard deviations. If the  $D^0 \rightarrow K^- \pi^+$  and  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  samples are fit separately, the resulting masses, widths, and relative yields of the  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  baryons are consistent within statistical errors. After accounting for selection efficiency and  $D^0$  branching fractions, the absolute yields for the two  $D^0$  decays modes are consistent for both the  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  baryons.

The above likelihood fit models the mass spectrum near  $2.84 \text{ GeV}/c^2$  as a smooth distribution [Fig. 2(a)]. There is, however, a nondistinct structure near a mass of  $2.84 \text{ GeV}/c^2$  whose origin is not understood, and so this model may not be accurate. Various modifications of the fit are employed as systematic checks. At one extreme, if the likelihood fit is limited to masses above  $2.8525 \text{ GeV}/c^2$  [Fig. 2(b)], the result is a substantial decrease (29%) in the  $\Lambda_c(2940)^+$  yield, a  $0.5 \text{ MeV}/c^2$  shift in mass, and a smaller width (12.5 MeV). The changes in the fitted  $\Lambda_c(2940)^+$  properties are much smaller if a third signal

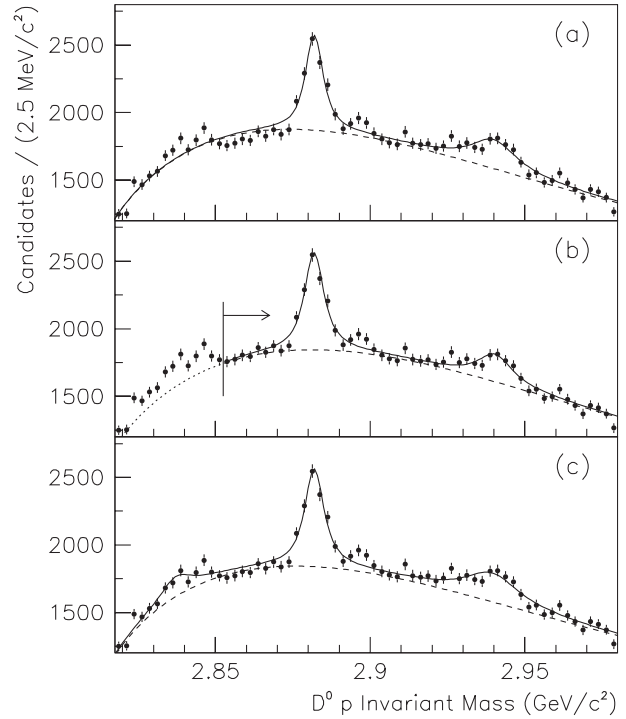


FIG. 2. Three examples of how the structure near a  $D^0 p$  mass of  $2.84 \text{ GeV}/c^2$  can be modeled. Shown are the results of fits that (a) assume a smooth distribution (as used for the central result), (b) exclude data below a mass of  $2.8525 \text{ GeV}/c^2$ , and (c) add an extra resonance contribution.

line shape (of variable mass and width) is added to the fit [Fig. 2(c)]. None of these alternate fits lead to a reduction in the statistical significance of the  $\Lambda_c(2940)^+$  signal below 7.2 standard deviations.

Because the  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  are only approximately 79 and 136  $\text{MeV}/c^2$  from  $D^0 p$  threshold, the systematic uncertainty in mass from possible detector biases is relatively small. This uncertainty is calculated by considering appropriate variations in the assumed  $B$  field strength and detector material using a procedure developed for measuring the  $\Lambda_c$  mass [7]. This procedure is also used to calculate small ( $< 0.1 \text{ MeV}/c^2$ ) corrections to the reconstructed  $D^0 p$  mass. An additional uncertainty of  $0.5 \text{ MeV}/c^2$  arises from the current knowledge of  $m_{D^0}$ . The results for the  $\Lambda_c(2940)^+$  baryon are

$$m = [2939.8 \pm 1.3(\text{stat}) \pm 1.0(\text{syst})] \text{ MeV}/c^2, \\ \Gamma = [17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst})] \text{ MeV}.$$

For the  $\Lambda_c(2880)^+$  baryon the results are

$$m = [2881.9 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})] \text{ MeV}/c^2, \\ \Gamma = [5.8 \pm 1.5(\text{stat}) \pm 1.1(\text{syst})] \text{ MeV}.$$

From the baryon yields obtained from the likelihood fits, the following ratio of production cross sections and decay



branching ratios is calculated

$$\frac{\sigma(\Lambda_c(2940)^+)\mathcal{B}r(\Lambda_c(2940)^+ \rightarrow D^0 p)}{\sigma(\Lambda_c(2880)^+)\mathcal{B}r(\Lambda_c(2880)^+ \rightarrow D^0 p)} = 0.81 \pm 0.13(\text{stat}) \pm 0.35(\text{syst}),$$

where the systematic uncertainty is dominated by uncertainties in the background shape.

Various tests are applied to the data to confirm the  $\Lambda_c(2940)^+$  signal. Since the signal is observed in two different  $D^0$  decay modes, it appears to be associated with real  $D^0$  decays. The lack of any structure in the  $D^0$  sideband samples and the relative size of these samples support this conclusion. Since the sample of protons is 83% pure, it is unlikely that the  $\Lambda_c(2940)^+$  signal could arise from proton misidentification. As further confirmation, when the  $K^+$  or  $\pi^+$  mass is assigned to the protons, the resulting  $D^0 K^+$  and  $D^0 \pi^+$  invariant mass distributions show no evidence of structure.

Even if the observed signal is attributed to a combination of  $D^0$  and protons, it is still possible to produce a false signal from the reflection of heavier states. One example of such a possible reflection is a hypothetical baryon of mass near  $3.10 \text{ GeV}/c^2$  decaying to either  $D^*(2010)^+ p$  or  $D^*(2007)^0 p$ . Such a baryon, if sufficiently narrow, would produce a  $D^0 p$  mass spectrum (after ignoring the  $\pi^+$  or  $\pi^0$  from  $D^*$  decay) of approximately the correct mass and width. Such a baryon would also be clearly visible in the  $D^*(2010)^+ p$  or  $D^*(2007)^0 p$  mass distributions. An explicit search in those mass distributions shows no signal, and thus this hypothesis is strongly disfavored.

Another possible reflection is from a baryon of mass  $3.13 \text{ GeV}/c^2$  decaying to  $D^0 \Sigma^+$ . The kinematics of such a decay could produce peaks at both  $2.85 \text{ GeV}/c^2$  and  $2.94 \text{ GeV}/c^2$  if the  $\Sigma^+$  had the appropriate spin alignment. The  $\Sigma^+$ , however, is a long-lived particle, and MC studies indicate that for this decay the proton vertex  $\chi^2$  probability distribution would peak at zero. An investigation of the  $\chi^2$  probability of the  $\Lambda_c(2940)^+$  signal seen in the data indicates a flat distribution. Thus, a reflection from  $D^0 \Sigma^+$  decay is also strongly disfavored.

The simplest interpretation of the  $\Lambda_c(2940)^+$  signal is that it arises from a charmed baryon of quark content  $cdu$ . Under this scenario the decay to  $D^0 p$  involves simple  $u\bar{u}$  gluon splitting. The remaining question is whether the  $\Lambda_c(2940)^+$  belongs to an isotriplet. The most direct way to address this question is to explicitly search for a neutral or doubly charged partner of nearly the same mass and width, analogous to the  $\Sigma_c^0$  and  $\Sigma_c^{++}$ . The BABAR detector cannot isolate the most obvious neutral decay mode ( $D^0 n$ ). It is possible, however, to search for a doubly charged baryon decaying to  $D^+ p$ .

To select a sample of  $D^+$  candidates, the same methods used for the  $D^0$  samples are applied to the decay  $D^+ \rightarrow K^- \pi^+ \pi^+$ . The selection requirements for the  $D^+ p$  sample

are  $|\Delta m| < 12 \text{ MeV}/c^2$ ,  $p^* > 2.7 \text{ GeV}/c$ , and  $\cos\vartheta < 0.8$ . The efficiency for this selection is approximately 23%.

The resulting  $D^+ p$  distribution is shown in Fig. 3. No signals corresponding to either the  $\Lambda_c(2880)^+$  or  $\Lambda_c(2940)^+$  baryon are apparent. A likelihood fit which assumes a doubly charged partner of the  $\Lambda_c(2940)^+$  of identical mass and width results in a yield of  $-40 \pm 120$  candidates (statistical error only).

Based on previous observations, such as the CLEO measurement of the  $\Sigma_c^0$  and  $\Sigma_c^{++}$  [8], one would expect similar production rates for the  $\Lambda_c(2940)^+$  and a hypothetical doubly charged partner. Under the additional assumption that the branching fraction of the doubly charged baryon to  $Dp$  is the same, the expected doubly charged signal yield would be approximately 2200 decays once the  $D^0$  and  $D^+$  branching fractions and selection efficiencies are accounted for (see Fig. 3). It thus seems unlikely that a doubly charged partner exists, unless its production is largely suppressed or it decays in an unexpected fashion.

The  $\Lambda_c(2940)^+$  baryon is interesting for several reasons. The  $DN$  decay mode, although not unexpected [9,10], is a final state that has received relatively little theoretical investigation. One observation which is notable, even if it might be a simple coincidence, is that at a mass of  $2939.8 \text{ MeV}/c^2$ , the  $\Lambda_c(2940)^+$  is just  $6 \text{ MeV}/c^2$  below the  $D^{*0} p$  threshold. It is also interesting that the  $\Lambda_c(2940)^+$  is approximately one pion mass heavier than the  $\Sigma_c(2800)^+$ , a charmed baryon recently discovered by BELLE [11] decaying to  $\Lambda_c \pi^0$ .

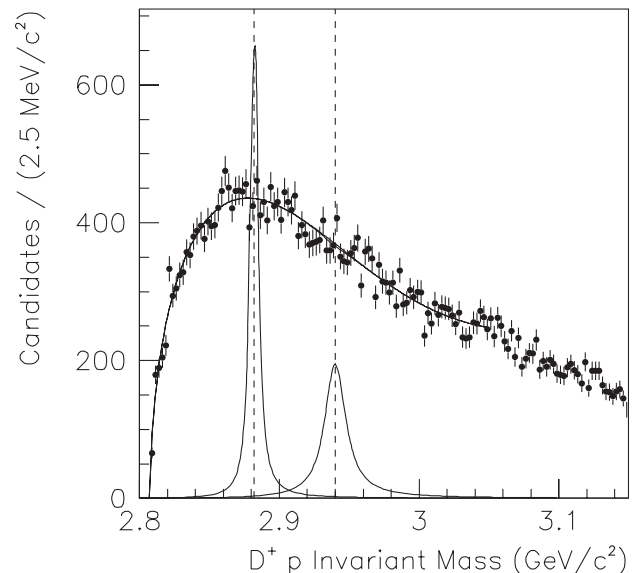


FIG. 3. The invariant mass distribution of selected  $D^+ p$  candidates. The curve is the result of the fit described in the text. The curves below are the line shapes of the  $\Lambda_c(2880)^+$  and  $\Lambda_c(2940)^+$  baryons obtained from the  $D^0 p$  data, drawn approximately to scale after correcting for selection efficiency and  $D^0$  and  $D^+$  branching fractions.

The  $\Lambda_c(2880)^+$  mass and width results presented here are consistent with but more precise than the CLEO measurement of  $m = 2880.9 \pm 2.3 \text{ MeV}/c^2$  and  $\Gamma < 8 \text{ MeV}$  (at 90% CL). The existence of the decay  $\Lambda_c(2880)^+ \rightarrow D^0 p$  rules out various interpretations of this baryon [10].

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