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Observation of a Charmed Baryon Decaying to D^0p at a Mass Near 2.94 GeV/c^2

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A search for charmed baryons decaying to D^0p reveals two states: the $\Lambda_c(2880)^+$ baryon and a previously unobserved state at a mass of [2939.8 ± 1.3 (stat.) ± 1.0 (syst.)] MeV/c^2 and with an intrinsic width of [17.5±5.2 (stat.)±5.9 (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 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 one of only two singly-charmed bayrons, 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^0p [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 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 $\Lambda_c(2880)^+ \to D^0p$ is also observed. The masses, intrinsic widths of both baryons and their relative production rate are measured.

The goal of this analysis is to study the inclusive D^0p 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 χ^2 probability of this fit is required to exceed 2%. Charged particle species (K^+, π^+, 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 χ^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^0p samples: Δm, the difference between the reconstructed D^0 mass and the accepted value of $m_{D^0} = 1864.6$ MeV/c^2 [1]; p^*, the center-of-mass momentum of the D^0p system; and $\cos\vartheta$, where ϑ is angle of the proton with respect to the e^+e^- system in the D^0p 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 ±1. Studies of Monte Carlo (MC) simulated data samples are used 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 $D^0 \to K^-\pi^+$ sample and $|\Delta m| < 9$ MeV/c^2, $p^* > 2.8$ GeV/c, and $\cos\vartheta < 0.8$ for the $D^0 \to K^-\pi^+\pi^-\pi^+$ sample. The Δm requirements correspond to approximately two standard deviations in D^0 mass resolution. The p^* requirement removes all sources of D^0p combinations from B meson decay.

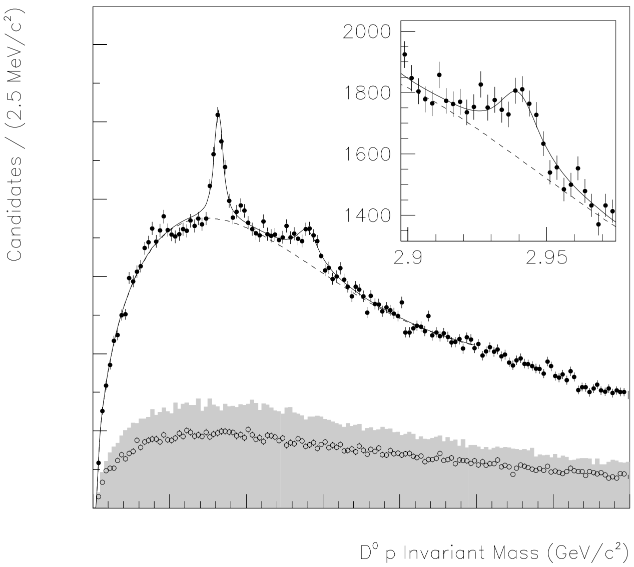

FIG. 1: The solid points are the D^0p invariant mass distribution of the final sample. Also shown are (gray) the contribution from false D^0 candidates estimated from D^0 mass sidebands and (open points) the mass distribution from wrong-sign $\overline{D}^0p$ candidates. The solid curve is the fit described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

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

To calculate a D^0p 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^0p invariant mass spectrum is shown in Fig. 1. Two peaks are apparent. The clear signal at 2.88 GeV/c^2 is likely due to the decay of the $\Lambda_c(2880)^+$ baryon. The signal at 2.94 GeV/c^2 is the evidence for the new $\Lambda_c(2940)^+$ baryon. No similar structures are observed in the wrong-sign $\overline{D}^0 p$ candidate combinations. Candidates selected from D^0 mass sidebands 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 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:

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

where Γ 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 MeV/c^2 and 1.3 MeV/c^2 for the $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^+ \pi^- \pi^+$ 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 ± 1.3 MeV/c^2, a width of 17.5 ± 5.2 MeV, and a raw yield of 2280 ± 310 decays (statistical errors only). The $\Lambda_c(2880)^+$ properties obtained are a mass of 2881.9 ± 0.1 MeV/c^2 and a width of 5.8 ± 1.5 MeV, consistent with the CLEO results [2], and a raw yield of 2800 ± 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 one degree of freedom) to a signal significance of 8.7 standard deviations. If the $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^+ \pi^- \pi^+$ 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 GeV/c^2 as a smooth distribution (Fig. 2(a)). There is, however, a non-distinct structure near a mass of 2.84 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 GeV/c^2 (Fig. 2(b)), the result is a substantial decrease (29%) in the $\Lambda_c(2940)^+$ yield, a 0.5 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 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.

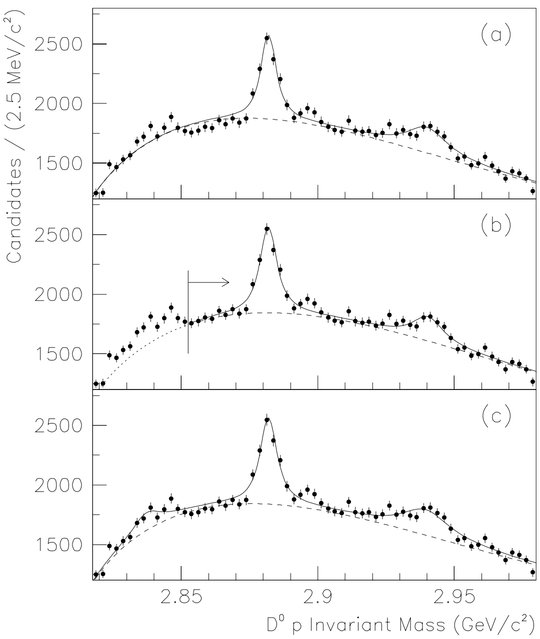

FIG. 2: Three examples of how the structure near a $D^0 p$ mass of 2.84 GeV/c^2 can be modeled. Shown are the results of fits that (a) assume a smooth distribution (as used for the central result) (b) exclude data below a mass of 2.8525 GeV/c^2, and (c) add an extra resonance contribution.

Because the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are near the $D^0 p$ 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 Λ_c mass [6]. This procedure is also used to calculate small (< 0.1 MeV/c^2) corrections to the reconstructed $D^0 p$ mass. An additional uncertainty of 0.5 MeV/c^2 arises from the current knowledge of m_{D^0}. The results for the $\Lambda_c(2940)^+$ baryon are:

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

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

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

From the baryon yields obtained from the likelihood fits, the following ratio of production cross sections and decay branching ratios is calculated:

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

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 mis-identification. As further confirmation, when the K^+ or π^+ mass is assigned to the protons, the resulting D^0K^+ 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 GeV/c^2 decaying to either $D^*(2010)^+p$ or $D^*(2007)^0p$. Such a baryon, if sufficiently narrow, would produce a D^0p mass spectrum (after ignoring the π^+ or π^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 $D^*(2007)^0p$ 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 GeV/c^2 decaying to $D^0\Sigma^+$. The kinematics of such a decay could produce peaks at both 2.85 GeV/c^2 and 2.94 GeV/c^2 if the Σ^+ had the appropriate spin alignment. The Σ^+, however, is a long-lived particle, and MC studies indicate that for this decay the proton vertex χ^2 probability distribution would peak at zero. An investigation of the χ^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^0p involves simple $u\overline{u}$ 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 Σ_c^0 and Σ_c^{++}. The *BABAR* detector cannot isolate the most obvious neutral decay mode (D^0n). 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 $D^+ \to K^-\pi^+\pi^+$. The selection requirements for the D^+p sample are $|\Delta m| < 12$ MeV/c^2, $p^* > 2.7$ GeV/c, and $\cos\vartheta < 0.8$. The efficiency for this selection is approximately 23%.

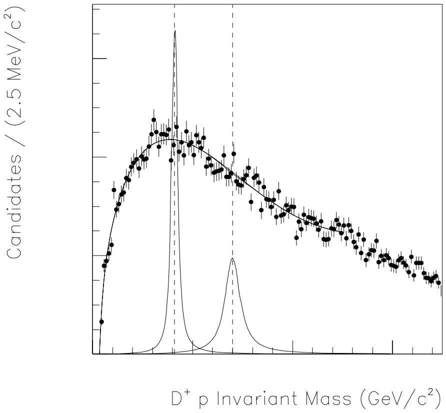

FIG. 3: The invariant mass distribution of selected D^+p candidates. The curve is the result of the fit described in the text. The curves below are the lineshapes of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ baryons obtained from the D^0p data, drawn approximately to scale after correcting for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

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 ± 120 candidates (statistical error only).

Based on previous observations, such as the CLEO measurement of the Σ_c^0 and Σ_c^{++} [7], 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. Relativistic quark model calculations [8] predict three excited Λ_c baryons of different spin-parity quantum numbers near a mass of 2.94 GeV/c^2. The DN decay mode, although not unexpected [9, 10], is a final state that has received relatively little theoretical investigation. If this baryon had a significant branching fraction to $\Lambda_c\pi^+\pi^-$ it probably would have been observed with the $\Lambda_c(2880)^+$ by CLEO [2]. It is not clear, however, why this particular decay mode, which is favored by phase space, is suppressed. One observation which is notable, even if it might be a simple coincidence, is that at a mass of 2939.8 MeV/c^2, the $\Lambda_c(2940)^+$ is just 6 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 $\Lambda_c\pi^0$.

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

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