Search for $\pi^+p \to \bar{D}^0C_1^{++}$ near threshold

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We have established an upper limit of 2.6 μb on the cross section times branching ratio for $\pi^+p \to \bar{D}^0C_1^{++}$ at a center-of-mass energy of 4.51 GeV. An upper limit of 1.4 μb is quoted for $\pi^+p \to \bar{D}^0C_1^{++}$, $C_1^{++} \to C_0^+\pi^+$. We estimate that the $\bar{D}^0C_1^{++}$ decay modes investigated are 15% of the total combined hadronic decays.

The discovery of the ψ, ψ' family of narrow states[1,2,3] and the subsequent observation of narrow structure in the $K\pi, K2\pi, K3\pi$ invariant-mass spectra[4,5] constitute strong evidence for the existence of a charmed quark.[6,7,8] There is also evidence for the production of baryons exhibiting the charm quantum number in photoproduction[9,10] and neutrino interactions.[11]

It then becomes important to search for the production of charmed particles in hadronic interactions. Theoretical predictions of charmed-particle production near threshold in πN interactions range from a few μb (Ref. 8) to a few nb.[12] The nonleptonic decays are expected to be a large fraction of the total decay rate[13,14] and the three- and four-body modes are predicted to be most important.[10,15]

The $\bar{D}^0, C_1^{++}$ (following the notation of Ref. 8) will not produce visible tracks in a bubble chamber but will appear as narrow signals in invariant-mass distributions, the $\bar{D}^0$ at a mass of 1865 MeV (Ref. 4) and the C_1^{++} at about 2420 MeV.[9,10] The presence of nearby C_1^* higher-spin states may turn this narrow signal into a rather broad one.[10]

Up to the present time charmed particles have not been seen in hadronic interactions. A previous bubble-chamber experiment[16] has quoted an upper limit of 3.0 μb for the cross section times branching ratio in π^+p interactions at a center-of-mass energy of 5.4 GeV. Experimental searches using other techniques have larger event samples but their sensitivity is generally not good in the most interesting mass region [i.e., $M(K\pi) < 2$ GeV]. Upper limits from these experiments are usually model dependent or refer to a specific kinematic region of the produced particles.[17]

We have data from a 580 000-picture exposure of the SLAC 82-in. bubble chamber using a π^+ beam at 10.3 GeV/c.[18] Using the visibility factors for K_S^0, Λ decays this corresponds to about 130 nb per observed event. The events were kinematically reconstructed and ambiguous fits were selected on the basis of the lowest χ^2 value in the highest constraint class. The center-of-mass energy is 4.51 GeV and puts us just above threshold for the reaction

$$\pi^+p \to \bar{D}^0C_1^{++}, \qquad (1)$$

where the cross section should be a maximum.[12]

To search for a possible signal from reaction (1) we used the final states

$$\Lambda K^0\pi^+\pi^+\pi^0,\quad \Lambda K^0\pi^+\pi^+\pi^+\pi^-,$$
$$\Lambda K^0\pi^+\pi^+\pi^+\pi^-\pi^0,\quad \Lambda K^+\pi^+\pi^+\pi^-,$$
$$\Lambda K^+\pi^+\pi^+\pi^-\pi^0,\quad \Lambda K^+\pi^+\pi^+\pi^+\pi^-\pi^-,$$
$$nK^+\bar{K}^0\pi^+\pi^+\pi^-,\quad pK^0\bar{K}^0\pi^+\pi^0,$$
$$pK^0\bar{K}^0\pi^+\pi^+\pi^-,\quad pK^0\bar{K}^0\pi^+\pi^+\pi^-\pi^0,$$
$$p\bar{K}^0K^+\pi^+\pi^-,\quad p\bar{K}^0K^+\pi^+\pi^-\pi^0,$$
$$pK^0K^-\pi^+\pi^+\pi^0,\quad pK^0K^-\pi^+\pi^+\pi^+\pi^-$$

arising from the Cabibbo-favored[8] decays

$$\bar{D}^0 \to K^0\pi^0, K^+\pi^-, K^0\pi^+\pi^-, K^+\pi^-\pi^0,$$
$$K^0\pi^+\pi^-\pi^0, K^+\pi^+\pi^-\pi^-;$$
$$C_1^{++} \to \Lambda\pi^+\pi^+, p\bar{K}^0\pi^+, \Lambda\pi^+\pi^+\pi^0, p\bar{K}^0\pi^+\pi^0,$$
$$n\bar{K}^0\pi^+\pi^+, pK^-\pi^+\pi^+.$$

The invariant mass of the possible decay products of the C_1^{++} were plotted against the invariant mass of the decay products of the $\bar{D}^0$ using a 25 MeV × 25 MeV bin size.[19] This amounted to a total of 5857 events in 38 separate plots. These were examined for an accumulation of events in the $\bar{D}^0, C_1^{++}$ overlap region.[20]

We did not observe any enhancement in this region which was not consistent with fluctuations in neighboring regions.[21] Figure 1 shows the two-dimensional plot for all of the final states combined.

To estimate upper limits on the production cross section times branching ratio we take the largest

MESON MASS (GeV): 1.6, 1.7, 1.8, 1.9, 2.0 (left to right); BARYON MASS (GeV): 2.6, 2.5, 2.4, 2.3 (top to bottom)

.4 ±.2	1.0 ±.5	.7 ±.3	1.1 ±.4	1.0 ±.3	.7 ±.3	.5 ±.2	.2 ±.1	1.3 ±.4	1.1 ±.5	.4 ±.2	.6 ±.3	.2 ±.2	0	0	0
.6 ±.2	1.1 ±.3	.6 ±.2	.9 ±.4	1.4 ±.4	1.3 ±.5	.9 ±.3	1.0 ±.4	.6 ±.3	.7 ±.3	.3 ±.2	.8 ±.4	.8 ±.4	.2 ±.1	0	0
.8 ±.3	.5 ±.2	.9 ±.3	.2 ±.1	.7 ±.3	.3 ±.2	.4 ±.2	.4 ±.2	.5 ±.2	1.4 ±.5	1.1 ±.4	1.0 ±.4	1.0 ±.3	1.0 ±.4	.9 ±.4	.3 ±.2
.8 ±.3	1.2 ±.4	.9 ±.3	.7 ±.3	.9 ±.3	.5 ±.3	1.4 ±.5	.4 ±.2	1.1 ±.4	1.0 ±.4	.8 ±.3	.8 ±.3	1.0 ±.5	.6 ±.3	.4 ±.2	.1 ±.1
1.0 ±.4	.5 ±.3	.9 ±.4	.6 ±.2	.5 ±.2	1.2 ±.4	1.1 ±.4	1.9 ±.5	1.6 ±.5	1.1 ±.4	.5 ±.2	1.6 ±.5	.2 ±.1	1.1 ±.4	1.6 ±.5	.4 ±.2
.8 ±.3	.7 ±.3	.6 ±.3	1.2 ±.4	.5 ±.3	1.6 ±.5	.6 ±.3	1.2 ±.4	.7 ±.3	1.1 ±.3	.8 ±.4	1.3 ±.4	.5 ±.2	.5 ±.2	.6 ±.3	.9 ±.3
.4 ±.2	1.0 ±.4	.5 ±.3	1.0 ±.4	1.5 ±.4	1.0 ±.4	.9 ±.3	.8 ±.3	.8 ±.3	1.0 ±.3	.5 ±.3	1.2 ±.4	.5 ±.2	1.2 ±.4	.7 ±.3	1.1 ±.3
.8 ±.4	.6 ±.3	.5 ±.2	.7 ±.2	1.2 ±.4	.3 ±.2	1.2 ±.4	.1 ±.1	.8 ±.3	.9 ±.4	1.6 ±.5	.5 ±.3	.4 ±.2	.7 ±.4	.9 ±.3	.8 ±.4
.5 ±.2	.4 ±.2	.2 ±.2	.7 ±.3	.9 ±.3	.9 ±.3	.6 ±.3	.5 ±.2	.5 ±.3	.8 ±.3	.7 ±.2	1.4 ±.4	.9 ±.4	.1 ±.1	.9 ±.4	.6 ±.2
.3 ±.2	1.1 ±.4	.9 ±.4	.5 ±.2	1.4 ±.4	.3 ±.2	1.4 ±.5	.7 ±.3	.8 ±.3	1.1 ±.3	.2 ±.2	.8 ±.4	.8 ±.3	.6 ±.2	1.0 ±.3	.9 ±.4
.7 ±.3	.2 ±.2	.1 ±.1	.9 ±.3	.5 ±.2	.6 ±.4	.5 ±.2	.8 ±.3	1.2 ±.4	.6 ±.3	.6 ±.3	.5 ±.3	.8 ±.3	1.3 ±.5	.4 ±.2	.9 ±.4
.1 ±.1	.6 ±.3	.8 ±.3	.9 ±.4	.3 ±.1	.7 ±.3	.4 ±.2	.5 ±.3	.3 ±.1	.6 ±.3	.2 ±.1	.7 ±.3	.8 ±.3	.3 ±.2	.3 ±.2	.7 ±.3

FIG. 1. Two-dimensional plot of the invariant mass of the decay products of the $\bar{D}^0$ vs the invariant mass of the decay products of the C_1^{++}. The entries are cross sections in units of μb.

number of events above background[22] in any four adjacent bins on the two-dimensional plot, within the $\bar{D}^0, C_1^{++}$ region.[20] From this we estimate a signal of 1.2 μb with a statistical error of 0.7 μb, leading to a 95% confidence-level upper limit to the cross section times branching ratio for reaction (1) of 2.6 μb. These four bins are indicated in Figs. 2(b), 2(e) and are outlined in Fig. 1. Figures 2(a), 2(c), 2(d), 2(f) show the regions immediately above and below these bins. They are fitted with quadratics and these curves are superimposed on Figs. 2(b), 2(e).

Based on the calculations of Refs. 10, 15 applied to our final states we estimate that the product of the $\bar{D}^0, C_1^{++}$ decay modes to which we are sensitive constitute approximately 15% of the total hadronic decays. This is about twice that of Ref. 16.

We have not observed clear evidence for the existence of reaction (1) in our data. Convincing evidence for reaction (1) would involve a statistically significant narrow enhancement in Fig. 2(b) together with a rather broad signal in Fig. 2(e) due to C_1, C_1^*. Although these features may be present in Figs. 2(b), 2(e) their statistical significance is not sufficient to warrant serious consideration.

Assuming the C_1^{++} is heavier than the C_0^+ by more than a pion mass[10] it can decay via the strong interaction

$$\pi^+ p \rightarrow \bar{D}^0 C_1^{++}, \quad C_1^{++} \rightarrow C_0^+ \pi^+. \tag{2}$$

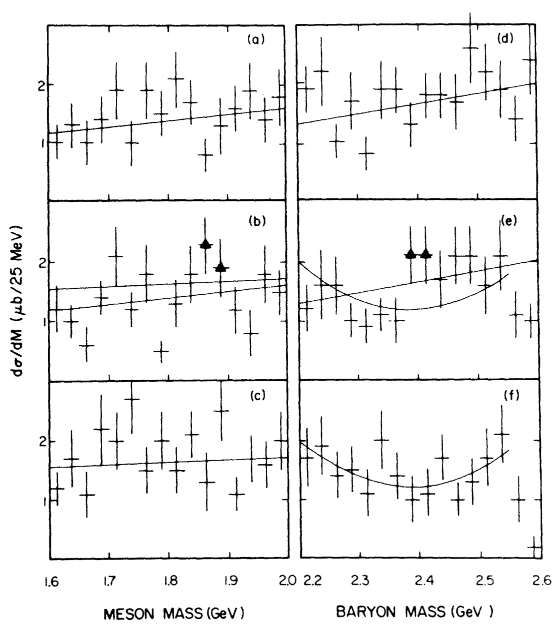

FIG. 2. Invariant-mass distribution of the decay products of the $\bar{D}^0$, C_1^{++} in the vicinity of the four bins indicated in Fig. 1. (b), (e) The four-bin enhancement region with background curves from (a), (c) and (d), (f) superimposed. The two bins indicated are the projection on this axis of the four-bin enhancement. (a), (d) Two-bin (i.e., 50 MeV) slices below and (c), (f) immediately above the four-bin enhancement, with fitted quadratic curves.

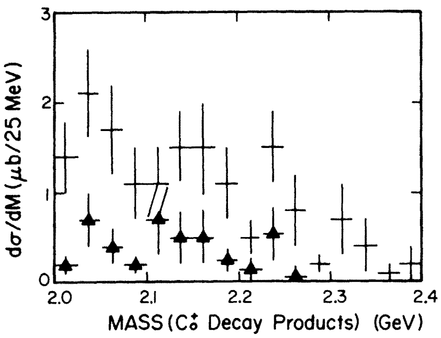

FIG. 3. Invariant-mass distribution of the possible decay products of the C_0^+. (a) + for 1.85 GeV < (mass of $\bar{D}^0$ decay products) < 1.9 GeV. (b) ▲ In addition 2.375 GeV < (mass of C_1^{++} decay products) < 2.45 GeV.

The branching fraction for this decay may be nearly one. Therefore, in an attempt to reduce our upper limit on the cross section we have examined the decay products of the C_1^{++} for evidence of this cascade decay. Figure 3 shows the invariant mass of all the possible decay modes of the C_1^{++} with a single π^+ excluded (i.e., the Cabibbo-favored decay modes of the C_0^+). The mass of the C_0^+ being about 2.26 GeV,[9,10] we take those events above 2.225 GeV in Fig. 3 (b) (4 events) and convert them to a 95% confidence level using the Poisson distribution. This gives a 95% confidence-level upper limit on the cross section times branching ratio for reaction (2) of 1.4 μb.

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[19]25 MeV represents our estimate of the experimental resolution.

[20]We define the overlap region where we might expect to see a signal as

$$1.825\ \text{GeV} < \text{mass (mesonic combinations)} < 1.9\ \text{GeV},$$

$$2.375\ \text{GeV} < \text{mass (baryon combinations)} < 2.45\ \text{GeV}.$$

[21]We have also looked for $\Sigma\pi$, $\Sigma 2\pi$, $\Sigma 3\pi$ decay modes of the C_1^{++} in 12 possible $\Sigma K n\pi$ ($n=2,3,4,5$) final states. There was a very small number of events and no signal was observed.

[22]The background is taken as the average number of events on the perimeter of the four bins.