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Review of Charmed Baryons in e^+e^- Annihilation*

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ABSTRACT

A resonance is observed in $pK^-\pi^+$, $\bar{p}K^+\pi^-$, pK_S^0 and $\bar{p}K_S^0$ invariant-mass spectra at 2.285 ± 0.006 GeV/c^2 which is associated with the lowest-lying charmed baryon (Λ_c). The Dalitz plot and limits on other modes and on the production of other states are presented. Measurements of inclusive p and Λ cross sections are also presented and allow an estimate of the branching ratios $B(\Lambda_c^+ \rightarrow pK^-\pi^+) = (2.2 \pm 1.0)\%$ and $B(\Lambda_c^+ \rightarrow p\bar{K}^0) = (1.1 \pm 0.7)\%$.

Evidence of charmed baryons being produced in e^+e^- annihilation first came in 1977 from the SLAC-LBL Mark I collaboration[1] in measurements of a rise in inclusive baryon production as a function of center of mass energy. Detection of a direct signal from a charmed baryon state, however, awaited the completion of the Mark II detector's one and a half years of running at SPEAR.[2] This occurred almost precisely one year ago and Fig. 1a shows the resulting mass spectrum[3] for the channel $pK^-\pi^+$ and charge conjugate $\bar{p}K^+\pi^-$. A significant enhancement was observed at $m(pK\pi) = 2.285$ GeV/c^2 in these channels which have the quantum numbers of the Cabibbo-favored weak decay of the Λ_c while no structure was observed in the channels $pK^-\pi^+$ and $pK^-\pi^-$ and their charge conjugates which do not have these quantum numbers (Fig. 1b). The data sample here consists of an integrated luminosity of 9150 nb^{-1} obtained at a center-of-mass energy 5.2 GeV and also from a scan of 4.5-6.0 GeV. Detailed descriptions of the Mark II detector and event reconstruction are given in reference 3. The curve in Fig. 1a shows that the data are well fitted by a Gaussian error function plus a background shape determined from a fit to Fig. 1b. The signal consists of 39 ± 8 events above a background of twenty events.

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Mass and Width Determination

The fit to Fig. 1a yields a mass of 2.286 ± 0.007 GeV/c^2 and an rms width of 0.010 GeV/c^2. The quoted error includes a systematic component of 0.006 GeV/c^2 due to uncertainties in the magnetic field and the geometric reconstruction. These error sources are checked by measurement of the $K^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ masses in the same data sample. A shift in the mass of the observed $pK\pi$ signal of 0.003 GeV/c^2, for example, would require a change in the magnetic field which would displace these masses from their present agreement with nominal values by 1 standard deviation.

A second mass determination which is subject to different systematic errors comes from those $pK\pi$ combinations which have total measured energy within 0.030 GeV of the beam energy. Figure 2 then plots the beam energy-constrained mass defined as $m_c = (E^2_{beam} - p^2_{pK\pi})^{1/2}$. An error which increases the magnitude of the momentum would cause an increase in the directly calculated mass of Fig. 1 but a decrease in the mass calculated with the beam energy constraint. The 10 ± 4 events observed in the peak in Fig. 2 yield a mass determination of 2.284 ± 0.008 GeV/c^2 and imply that the simple reaction $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ is the source of (26 ± 11)% of the observed $pK\pi$ signal. From the combination of the two mass determinations our best estimate of the mass of the charmed baryon is 2.285 ± 0.006 GeV/c^2.

As expected for the weak decay of a charmed baryon, the measured width agrees with the calculated detector resolution, providing a limit $\Gamma_{\Lambda_c} < 0.020$ GeV/c^2 (90% C.L.).

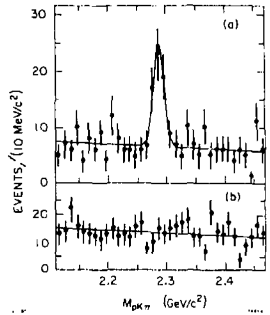

Fig. 1(a) The combined $pK^-\pi^+$ and $\bar{p}K^+\pi^-$ mass distribution for recoil masses greater than 2.2 GeV/c^2. (b) As (a) but for $pK^+\pi^-$, $pK^-\pi^-$ and their charge conjugates.

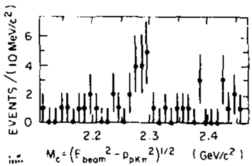

Fig. 2 The beam-energy-constrained mass d[illegible]ution for events with pK^-[illegible]π^- energy within 0.03 [illegible] the beam energy.

Dalitz Plo[illegible]

Figure 3 shows the Dalitz plot for the events in the peak. The projections of this plot along with that for sideband control regions are

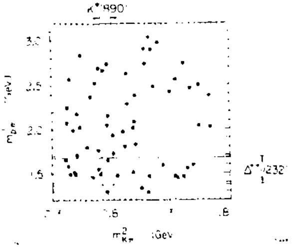

Fig. 3 Dalitz plot for events in pKπ peak region.

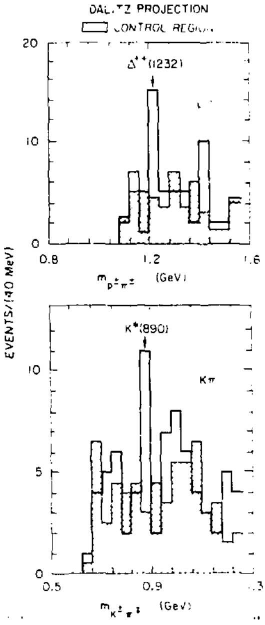

Fig. 4 Projections of the Dalitz plot with data also plotted from control regions off the peak.

more informative and are plotted in Fig. 4. They tell us the fraction of the observed $pK^-\pi^+$ events which are resonant are (17 ± 7)% and (12 ± 7)% for the $\Delta^{++}(1232)$ and the $K^*(890)$, respectively.

Other Decay Modes

We have searched for other decay modes of the charmed baryon in a number of different channels. Figure 5 shows the pK^0_S invariant mass distribution which features a signal containing 12.5 ± 4.5 events at a mass value in good agreement with that of the pKπ. This yields a branching ratio for $\Lambda_c^+ \to p\bar{K}^0$ relative to that for $\Lambda_c^+ \to pK^-\pi^+$ of 0.5 ± 0.25, fully corrected. This is the only channel other than pKπ where we have been able to observe a significant signal. To reduce background, one can use the fact that approximately one quarter of the events come from the two-body process $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ to plot the beam energy-constrained mass as is done in Fig. 6 with somewhat looser cuts than in Fig. 2. These plots provide upper limits on the $\Lambda_c \to \Lambda\pi$ and $\Lambda_c \to \Lambda 3\pi$ branching ratios relative to the branching ratio $\Lambda_c \to pK\pi$ of <0.8 and <1.4, respectively, at the 90% confidence level.

Higher Mass Charmed Baryons

Figure 7 shows a plot of the mass recoiling against the observed $pK\pi$ and pK_S^0 signals along with indications of the regions expected to be populated if the processes $e^+e^- \to \Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Sigma}_c^*$ and $\bar{\Sigma}_c^*\bar{\Sigma}_c^*$ accounted for the ~75% of the observed cross section which is not $e^+e^- \to \Lambda_c\bar{\Lambda}_c$. The mass differences used here, also indicated in Fig. 7, are what is expected from SU(4) mass formulas.[4] The only conclusion that can be drawn from this is that it is unlikely that any single one of these processes is dominant.

One can try to reconstruct the cascade directly in the data

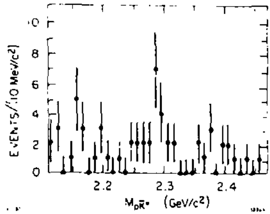

Fig. 5 The combined pK_S^0 and $\bar{p}K_S^0$ mass distribution for recoil masses greater than 2.2 GeV/c².

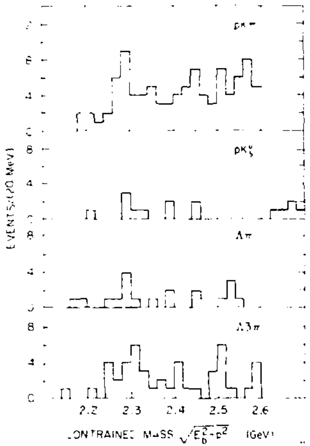

Fig. 6 The beam-energy-constrained mass distributions for several channels with looser cuts than in Fig. 2

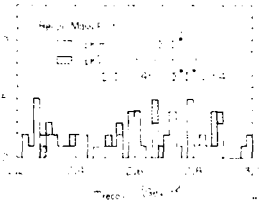

Fig. 7 Distribution of recoiling mass against $pK\pi$ and $p\bar{K}^0$ combinations in the peak regions.

and look at the mass difference $\Delta m = m(pK^-\pi^+\pi^+) - m(pK^-\pi^+)$ as was done in Reference 5 but the cascade pion is, in general, of too low momentum (~.070 GeV/c) to be tracked successfully in the Mark II detector However, hand scanning and measurement of our Λ_c events has revealed a number of such untracked "loopers" which is about twice as large as the number which come per event from sideband control regions and whose reconstructed mass differences may have a tendency to cluster at mass differences near $\Delta m = 0.160$ GeV/c. The statistics, *however, are inadequate and* one will have to wait for this type of analysis in e^+e^- until the Mark III has accumulated sufficient data in the future.

If the Σ_c mass is less than $m_{\Lambda_c} + m_\pi$, the Σ_c^{++} and Σ_c^0 could have direct weak decays. No evidence is found for any such effect in the $pK2\pi$, pK^0, $\Lambda 2\pi$ and $\Lambda 4\pi$ channels at the level of approximately 25-60% of the observed $pK\pi$ signal (90% C.L.).

Strange charmed baryons have been searched for, and not found, in ΛK^0 and pK^-K^0 with limits on $\sigma \cdot B$ of the order of 50-80% of that for the observed $pK\pi$ state. These limits are much larger than the rates that probably would be expected.

Estimate of the Branching Ratio $B(\Lambda_c \to pK\pi)$

We are able to use our inclusive measurements of p *and* Λ *produc*tion as a function of energy to estimate the total production of charmed baryons. Figure 8 presents these measurements as $R(p+\bar{p}) = 2\sigma(\bar{p})/\sigma_{\mu\mu}$ and $R(\Lambda+\bar{\Lambda}) = [\sigma(\Lambda) + \sigma(\bar{\Lambda})]/\sigma_{\mu\mu}$ where the estimated overall systematic errors of ±17% and ±27%, respectively, are not included. We observe clear steps in both $R(p+\bar{p})$ and $R(\Lambda+\bar{\Lambda})$ in the range 4.5 to 5.2 GeV center-of-mass energy compatible with the interpretation of the observed $pK\pi$ signal as the lowest-lying charmed baryon. We make the following assumptions (see reference 3): (i) The observed step in $R(p+\bar{p})$ is due entirely to the onset of charmed baryon pair production; (ii) all charmed baryons cascade down to the Λ_c state;[6] and (iii) the probability for a charmed baryon to give a proton (as opposed to a neutron) as a final product[7] is 0.6 ± 0.1. Then

$$\sigma(\Lambda_c+\bar{\Lambda}_c) = \frac{\Delta R(p+\bar{p})}{0.6} \cdot \sigma_{\mu\mu}$$

and the measured step size $\Delta R(p+\bar{p}) = 0.31 \pm 0.06$ gives the inclusive charmed baryon cross section at 5.2 GeV to be $\sigma(\Lambda_c+\bar{\Lambda}_c) = 1.7 \pm 0.4$ nb. Using the measured $\sigma(\Lambda_c+\bar{\Lambda}_c) \cdot B(\Lambda_c \to pK\pi)$ at 5.2 GeV for the observed signal of 0.037 ± 0.012 nb, the branching ratios themselves can then be estimated to be

$$\begin{aligned} B(\Lambda_c \to pK\pi) &= (2.2 \pm 1.0)\% \\ B(\Lambda_c \to p\bar{K}^0) &= (1.1 \pm 0.7)\% \\ \left.\begin{aligned} B(\Lambda_c \to \Lambda\pi) &< 1.8\% \\ B(\Lambda_c \to \Lambda 3\pi) &< 3.1\% \end{aligned}\right\} & \; 90\% \text{ C.L.} \end{aligned}$$

It should be mentioned that study of the systematic errors in the data of Fig. 8 imply that a slower rise in $R(p+\bar{p})$ in the region 5.2-7.4 GeV above the step is significant. This may suggest, but certainly does not require, the opening of new higher mass charmed baryon channels.

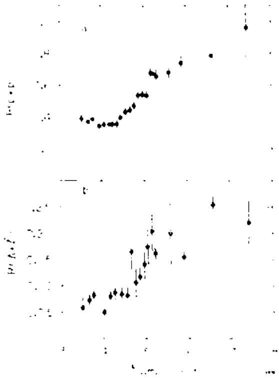

Fig. 8(a) $R(p+\bar{p})$ as a function of $E_{c.m.}$ (b) $R(\Lambda+\bar{\Lambda})$ as a function of $E_{c.m.}$ Errors are statistical only.

Λ/p Ratio

The Λ/p ratio for all charmed baryon decays can be estimated from the relative step sizes in Fig. 8. Using $\Delta R(\Lambda+\bar{\Lambda}) = 0.10 \pm 0.03$ with $\Delta R(p+\bar{p})$ from above, we get a Λ/p ratio of (41 ± 15)% after explicitly removing protons which arise from Λ decay, but not from other weakly decaying strange baryons. This ratio is in excellent agreement with the prediction of 43% by Körner, Kramer and Willrodt[8] but their resonance dominance model assumptions may not be consistent with the low resonance fractions given here from the Dalitz plot.

Conclusion

It should be pointed out that the data presented here come principally from 3 1/2 weeks running at 5.2 GeV center-of-mass energy at SPEAR. One can hope, therefore, that substantial new information from e^+e^- on higher mass states and other decay modes will be provided by a long (~6 month) run at that energy by our successor in the SPEAR West Pit, the Mark III detector.

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6. This neglects weak decays from all other charmed baryons, consistent with predictions and present experimental information.

7. From our measurement of $\Delta R(\Lambda+\bar{\Lambda})$ and $\Delta R(p+\bar{p})$ and a simple isospin statistical model.

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