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Charmed-baryon interpretation of $\bar{\Lambda}\pi^-\pi^-\pi^+$ and $\bar{\Lambda}\pi^-\pi^-\pi^+\pi^\pm$ peaks

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The $\bar{\Lambda}3\pi(2250)$ and $\bar{\Lambda}4\pi(2500)$ peaks recently discovered in photoproduction are interpreted as charmed antibaryons. Specifically it is suggested that the $\bar{\Lambda}3\pi(2250)$ is the charmed analog of $\Lambda(1115)$ and decays weakly. Quantum-number and spin-parity assignments are discussed briefly. We give isospin relations and predictions for the mean multiplicity of nonleptonic decay products, with special attention to channels detectable in existing experiments. A strategy for studying the dynamics of multibody nonleptonic decays is outlined and an interesting soft-pion theorem is recalled. Semileptonic decays are mentioned in passing. The $\bar{\Lambda}4\pi(2500)$ is interpreted as an amalgam of the charmed analogs of $\Sigma(1192)$ and $Y_1^*(1385)$; the shape of its two-peak structure is deduced. Prospects for the observation of additional charmed baryons are considered.

I. INTRODUCTION

Experimental observations over the past two years point to the existence of a new family of hadrons. The newly discovered particles bear striking resemblance to the charmed particles[1,2] required in gauge theories to describe weak neutral currents correctly. Among the mesons, the usual nonets of SU(3) are expanded to hexadecimets of SU(4) by the addition of an SU(3) triplet of particles composed of a charmed quark and an ordinary antiquark, a triplet of antiparticles, and an SU(3)-singlet hidden charm state composed of a charmed quark and a charmed antiquark. The baryon spectrum is similarly enriched. Octets and decimets of SU(3) are expanded to (inequivalent) 20-dimensional representations of SU(4) by the addition of the states listed in Tables I and II.

TABLE I. Charmed $\frac{1}{2}^+$ baryon states. (The notations $\{ab\}$ and $[ab]$ denote symmetric and antisymmetric combinations, respectively.)

Label	Quark content	Charm	SU(3)	Isospin (I, I_z)	Strangeness
C_0^+	$c[ud]$	1	$\underline{3}^*$	(0, 0)	0
A^+	$c[su]$			$(\frac{1}{2}, \frac{1}{2})$	-1
A^0	$c[sd]$			$(\frac{1}{2}, -\frac{1}{2})$	
C_1^{++}	cuu	1	$\underline{6}$	(1, 1)	0
C_1^+	$c\{ud\}$			(1, 0)	
C_1^0	cdd			(1, -1)	
S^+	$c\{su\}$			$(\frac{1}{2}, \frac{1}{2})$	-1
S^0	$c\{sd\}$			$(\frac{1}{2}, -\frac{1}{2})$	
T^0	css			(0, 0)	-2
X_u^{++}	ccu	2	$\underline{3}$	$(\frac{1}{2}, \frac{1}{2})$	0
X_d^+	ccd			$(\frac{1}{2}, -\frac{1}{2})$	
X_s^+	ccs			(0, 0)	-1

The lowest-lying charmed baryons are expected to be more massive than the lowest-lying charmed mesons. The mesons, being stable against strong (and electromagnetic) decays, must decay weakly. It is extremely likely that the nonleptonic decays $D^0(c\bar{u}) \to K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ and $D^+(c\bar{d}) \to K^-\pi^+\pi^+$ are the signals observed[3] at SPEAR. There is considerable circumstantial evidence for semileptonic decays of these objects as well.[4] It was not *a priori* obvious whether charmed baryons should be so massive as to decay strongly into charmed mesons and ordinary baryons or so light as to be stable against such decays. However, the event

$$\nu p \to \mu^-\Lambda\pi^+\pi^+\pi^+\pi^- \tag{1}$$

observed at Brookhaven[5] can be interpreted as the production and subsequent weak decay of a charmed baryon. Interpreted instead in the absence of charm, this event would mark the first instance of a semileptonic process with $\Delta S = -\Delta Q$.

TABLE II. Charmed $\frac{3}{2}^+$ baryon states.

Label	Quark content	Charm	SU(3)	Isospin (I, I_3)	Strangeness
C_1^{*++}	cuu	1	$\underline{6}$	(1, 1)	0
C_1^{*+}	cud			(1, 0)	
C_1^{*0}	cdd			(1, -1)	
S^{*+}	cus			$(\frac{1}{2}, \frac{1}{2})$	-1
S^{*0}	cds			$(\frac{1}{2}, -\frac{1}{2})$	
T^{*0}	css			(0, 0)	-2
X_u^{*++}	ccu	2	$\underline{3}$	$(\frac{1}{2}, \frac{1}{2})$	0
X_d^{*+}	ccd			$(\frac{1}{2}, -\frac{1}{2})$	
X_s^{*+}	ccs			(0, 0)	-1
Θ^{++}	ccc	3	$\underline{1}$	(0, 0)	0

Recently a peak has been observed[6] at 2250 MeV/c^2 in the effective-mass distribution of $\bar{\Lambda}\pi^-\pi^-\pi^+$ produced in the reaction

$$\gamma + \mathrm{Be} \to \bar{\Lambda} + \text{pions} + \cdots . \tag{2}$$

The mass coincides with one of the $\Lambda\pi^+\pi^+\pi^-$ combinations in event (1). There is in addition an indication of a state near 2500 MeV/c^2 which decays into $\pi^\pm + (\bar{\Lambda}\pi^-\pi^-\pi^+)$.

In this paper we shall discuss some consequences of a charmed-baryon interpretation of the new photoproduction data. We identify the $\bar{\Lambda}\pi^-\pi^-\pi^+$ peak as the nonleptonic decay of the spin-$\frac{1}{2}$ isoscalar $\bar{C}_0$. The suggested peak at 2500 MeV/c^2 will be identified as the combined effect of the decays $\bar{C}_1 \to \bar{C}_0\pi$ and $\bar{C}_1^* \to \bar{C}_0\pi$.

The order of presentation of our remarks is as follows. We deal in Sec. II with weak decays of[7] C_0^+, with attention to multiplicities and relative rates. Photoproduction of C_0, C_1, and C_1^* occupies Sec. III. In Sec. IV we take up masses and widths of C_1 and C_1^*, and discuss the $(\bar{\Lambda}4\pi)$ spectrum to be expected in photoproduction. We pay brief attention to spin-parity determinations in Sec. V. Possibilities for observing other charmed baryons are treated in Sec. VI. Our conclusions and parting questions occupy Sec. VII.

The learned reader will find much here that is familiar. Our intent has been to gather together information on charmed baryons which will be useful in pursuing the new experimental leads.

II. WEAK DECAYS OF CHARMED BARYONS

A. General observations

In the Glashow-Iliopoulos-Maiani (GIM) charm scheme, the Cabibbo-favored weak transition is

$$c \to su\bar{d} \ , \tag{3}$$

for which $\Delta S = -1$, $\Delta I = 1$, and $\Delta I_z = 1$. As a consequence the most important nonleptonic decays of the isosinglet C_0^+ are into states with the quantum numbers of suu, i.e. of Σ^+, and with total isospin 1. The final states thus should appear to be members of an *incomplete isospin multiplet* which signals their origin in a weak decay process. This is indeed the case for the data reported in Ref. 6, wherein the peak observed in $\bar{\Lambda}\pi^-\pi^-\pi^+$ is not accompanied by a peak in $\bar{\Lambda}\pi^+\pi^+\pi^-$. The particles C_1 and C_1^* may, depending upon their masses, decay strongly into $C_0 + \pi$ or through the weak interaction. In either case, the ultimate decay products must have the quantum numbers $S = -1$, $I \leqslant 2$, and $Q = 0$, 1, or 2. They will, therefore, appear to belong to an incomplete isospin multiplet. Again, the data of Ref. 6 are consistent with these requirements.

The Cabibbo-favored two-body decays[8] of C_0^+ lead to the final states $\bar{K}^0 p$, $\pi^+\Lambda$, $\pi^+\Sigma^0$, $\pi^0\Sigma^+$, $\eta\Sigma^+$, $\eta'\Sigma^+$, and $K^+\Xi^0$. Even an assumption more detailed than (3), namely "sextet enhancement," does not fix the relative rates into these channels, but does yield useful triangle relations. It is of interest to remark that an emulsion event reported in Ref. 9 is consistent (on the basis of lifetimes and effective masses) with the production of $C_0^+\bar{C}_0^-$ and subsequent decay into $\pi^0 +$ charged Σ or $\bar{\Sigma}$ and $\eta +$ charged $\bar{\Sigma}$ or Σ. In a charged-particle detector, only the $K_S p$ and $\pi^+\Lambda$ modes can be observed. This fact, with the experimental observation of the putative C_0^+ in a four-body mode, prods us to consider multibody decay channels.

B. Multiparticle nonleptonic decays

The observation of a peak in the $\bar{\Lambda}\pi^-\pi^-\pi^+$ spectrum at 2250 MeV/c^2 impels us to regard the $\Lambda\pi^+\pi^+\pi^-$ combination with similar mass of Ref. 5 as an example of C_0^+ decay. So interpreted, the BNL event would be the first known instance of a four-body nonleptonic decay. We shall use it as an example to lend concreteness to our discussion.

How do multibody nonleptonic decays occur? To gain some insight into the kinematical structure of the event and to depict it readily on paper we have performed a principal-axis transformation on the three-momentum vectors of the products, in the C_0^+ rest frame. The result is shown in Fig. 1. In momentum space the event has the shape of a tripod or music stand with the three legs being $\Lambda\pi^+\pi^+$ and the upright rod being π^-. The eigenvalues of the moment-of-inertia matrix

$$\mathfrak{M}_{ij} = \sum_n p_i^{(n)} p_j^{(n)} \tag{4}$$

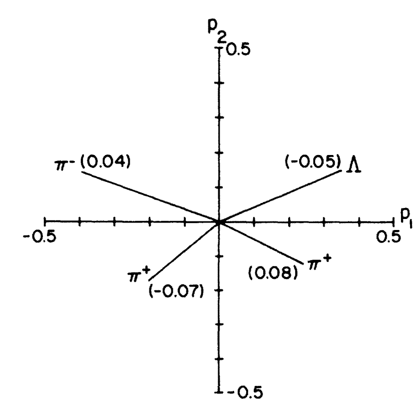

FIG. 1. Principal-axis projection of the $\Lambda\pi^+\pi^+\pi^-(2244)$ combination from the BNL neutrino event (Ref. 5). The numbers in parentheses are projections on the third principal axis. All momenta are in GeV/c.

(the sum runs over the decay products and $i,j = x,y,z$) are

$$(\lambda_1,\lambda_2,\lambda_3)=(0.38,0.09,0.02)\ (\mathrm{GeV}/c)^2\,, \tag{5}$$

corresponding to eigenvectors p_1,p_2,p_3. We define a sphericity parameter

$$\sigma=(\lambda_2+\lambda_3)/2\lambda_1 \tag{6}$$

which ranges between 0 (for collinear configurations) and 1 (for spherical configurations). For this event, $\sigma=0.14$.

The configuration of the BNL event is reminiscent of a theorem[10] which forbids emission of a soft π^-.[11] The soft-pion theorem can be visualized as follows: In the absence of pole terms[12] the emission of soft pions is calculated by attaching them in all possible ways to the quarks in the nonleptonic weak Hamiltonian. There is no way to join an outgoing π^- to the quarks in $c\to su\bar{d}$, whereas π^+ and π^0 can be attached. The soft-π^- theorem or the music-stand picture also requires low effective masses for $\pi^+\pi^+$ and for $\Lambda\pi^+$ as noted in Table III. Needless to say, it is of great interest to confront the soft-pion theorem with a larger data sample.

The principal-axis projection of Fig. 1 was motivated in part by the desire to search for jetlike structure in the multibody decay. The distribution in sphericity for decays according to phase space alone is shown in Fig. 2. In the absence of specific dynamics, the expected sphericity is already quite small: $\langle\sigma\rangle\simeq 0.15$. Consequently the nearly coplanar appearance of the BNL event is not of itself remarkable.

TABLE III. Effective-mass combinations for the BNL event $\nu p\to\mu^-\pi_0^+(\pi_1^+\pi_2^+\pi^-\Lambda)$ (see Ref. 5).

Combination	Effective mass (MeV/c^2)
$\pi_1^+\pi_2^+\pi^-\Lambda$	2244
$\pi_1^+\pi_2^+\pi^-$	983
$\pi_1^+\pi^-\Lambda$	1906
$\pi_2^+\pi^-\Lambda$	1922
$\pi_1^+\pi_2^+\Lambda$	1757
$\pi_1^+\pi_2^+$	542
$\pi_1^+\pi^-$	435
$\pi_2^+\pi^-$	728
$\pi_1^+\Lambda$	1478
$\pi_2^+\Lambda$	1380
$\pi^-\Lambda$	1597

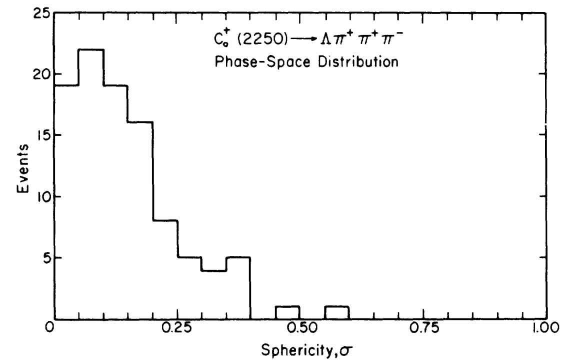

FIG. 2. Phase-space distribution in sphericity for 100 simulated decays $C_0^+(2250)\to\Lambda\pi^+\pi^+\pi^-$.

We do expect that the mass of the $C_0^+(2250)$ is probably too low for jets to develop. Jetlike configurations become apparent in electron-positron annihilations[13] at c.m. energies between 3 and 6 GeV. It may therefore be profitable to regard low-mass multibody decays as three-dimensional and very-high-mass multibody decays as one-dimensional.[14] (Thus the multibody decays of particles composed of quarks heavier than the charmed quark may well exhibit jetlike characteristics.) This attitude leads us to an alternative model for the multiparticle decay of an object with mass less than 3 GeV/c^2. In a version[15] of the Fermi statistical model[16] appropriate to particle decay, the mean multiplicity of decay products is

$$\langle n\rangle = n_0+\left(\frac{4}{\pi}\right)^{1/4}\frac{\zeta(3)}{[3\zeta(4)]^{3/4}}\left(\frac{E}{E_0}\right)^{3/4} = n_0+0.528(E/E_0)^{3/4}\,. \tag{7}$$

Here E is the energy available in excess of the rest masses of the lowest-multiplicity (n_0) decay channel. For the decays $C_0^+\to\Lambda+\pi^++(m\text{ pions})^0$, $E=(M_{C_0}-M_\Lambda-M_\pi)c^2$ and $n_0=2$. The scale E_0 is given by the hadronic radius R_0:

$$E_0\equiv\hbar c/R_0\,. \tag{8}$$

For a radius of 1 fm (typical of bag models of hadrons[17]), $E_0\simeq 0.2$ GeV.

Application of Eq. (7) to charmed-particle decays of interest yields the multiplicity estimates given in Table IV. If we further assume the particles in excess of n_0 to be Poisson distributed, we obtain the estimates of the relative importance of various decay channels given in Figs. 3–6. These estimates are especially crude, as we have made no attempt to incorporate constraints of angular momentum conservation or of charge conservation.[18] Figure 4 shows that the decay mode $\Lambda\pi\pi\pi$ is indeed quite probable. The charge state $\Lambda\pi^+\pi^+\pi^-$ must make up at least $\frac{1}{2}$ but not more than $\frac{4}{5}$ of the total $\Lambda\pi\pi\pi$ signal.[19] The $\Lambda\pi^+$ mode should be

TABLE IV. Mean multiplicities of charmed-particle decays in the Fermi statistical model[a] of Eq. (7).

Class of decays	Mean total multiplicity
$D^0(1865) \to \bar{K}\pi$ + pions	4.07
$C_0^+(2250) \to \Lambda\pi^+$ + pions	3.76
$\to \Sigma\pi$ + pions	3.66
$\to \bar{K}N$ + pions	3.52
$A(2470)$[b] $\to \Xi\pi$ + pions	3.78
$\to \Lambda\bar{K}$ + pions	3.57
$\to \Sigma\bar{K}$ + pions	3.47
$T(2730)$[b] $\to \Omega^-\pi^+$ + pions	3.65
$\to \Xi\bar{K}$ + pions	3.65

[a] Estimates are based on $E_0 = 0.2$ GeV.
[b] Mass estimated as in Ref. 26, adjusted to fit $M(C_0) = 2250$ MeV/c^2.

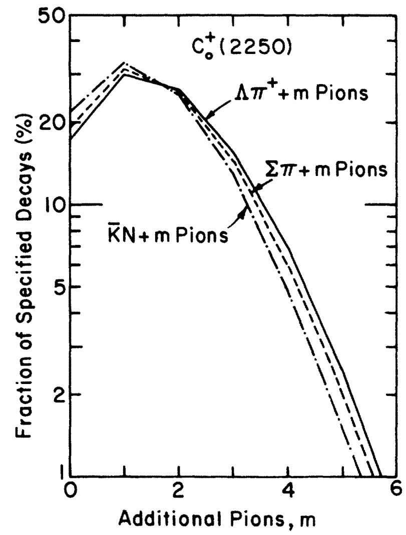

FIG. 4. Same as Fig. 3 for the decays of $C_0^+(2250)$ into $\Lambda\pi^+ + m$ pions, $\Sigma\pi + m$ pions, and $\bar{K}N + m$ pions.

observable as well. The decay $C_0^+ \to \Lambda\pi\pi$ always involves a neutral pion; it will go undetected in the apparatus of Ref. 6. In the Σ + pions channel, we expect the $\Sigma\pi\pi$ decays to be prominent. The charged modes $\Sigma^-\pi^+\pi^+$ and $\Sigma^+\pi^+\pi^-$ must account for between $\frac{1}{2}$ and $\frac{4}{5}$ of the $\Sigma\pi\pi$ rate.[19] Finally, we note that in the $\bar{K}N$ case some observable decay modes of C_0^+ will be $K_S p$ and $K^-p\pi^+$. There is no lower bound on the fraction of $\bar{K}N\pi$ decays in the $K^-p\pi^+$ charge state; the upper bound is $\frac{3}{4}$.[19]

C. Semileptonic decays

The Cabibbo-favored semileptonic decays[20] of the stable charmed baryons are, in simplest form,

$$
\begin{aligned}
&C_0^+ \to \Lambda l^+\nu\,,\\
&A^+ \to \Xi^0 l^+\nu\,,\\
&A^0 \to \Xi^- l^+\nu\,,\\
&T^0 \to \Omega^- l^+\nu\,.
\end{aligned}
\tag{9}
$$

The hadronic transitions obey the selection rules $\Delta C = -1$, $\Delta S = -1$, $\Delta Q = -1$, and $\Delta I = 0$. It is of interest to estimate the relative importance of multihadron decays. On the basis of our earlier discussion of nonleptonic decays we guess the relation between hadronic energy and the mean multi-

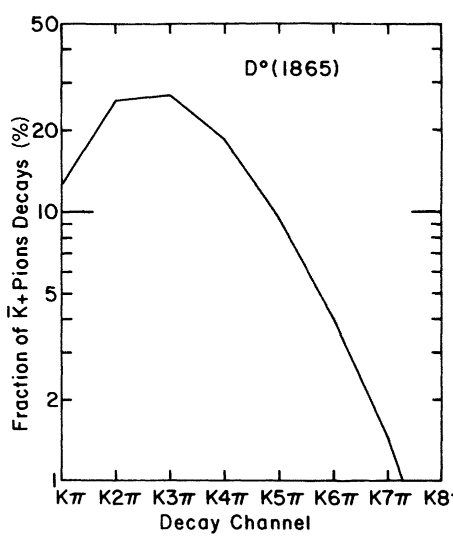

FIG. 3. Relative importance of various multibody decays of $D(1865) \to K + m$ pions according to the statistical model discussed in the text.

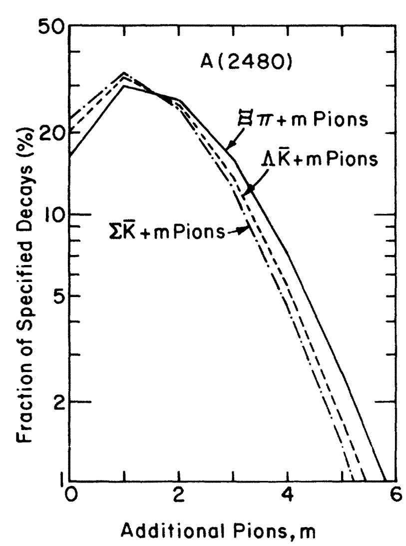

FIG. 5. Same as Fig. 3 for the decays of $A(2480)$ into $\Xi\pi + m$ pions, $\Lambda\bar{K} + m$ pions, and $\Sigma\bar{K} + m$ pions.

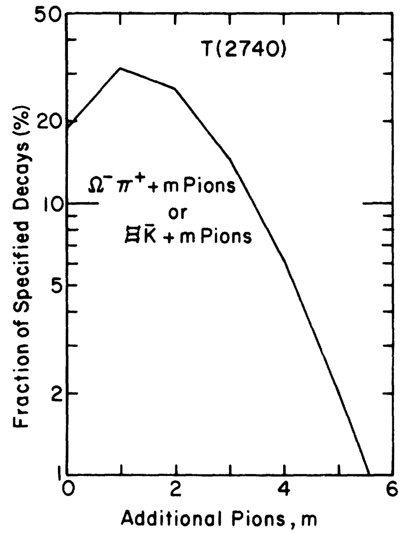

FIG. 6. Same as Fig. 3 for the decays of $T(2740)$ into $\Omega^-\pi^+ + m$ pions or $\Xi\bar{K} + m$ pions.

plicity:

$$\langle n(Q)\rangle = 1 + 0.528\left(\frac{Q}{E_0}\right)^{3/4}, \tag{10}$$

where for C_0 decay

$$Q = (M_{C_0} - M_\Lambda)c^2 - \text{energy carried by leptons}$$
$$= \text{energy carried by hadrons} - M_\Lambda c^2 .$$

Evidently, reliable hadron calorimetry is a prerequisite for testing this conjecture.

III. ELECTROMAGNETIC PRODUCTION OF CHARMED-BARYON PAIRS

It is tempting to assume[2,21] that the photoproduction of charmed-particle pairs near threshold is dominated by the $c\bar{c}$ part of the current. If this is so, the diffractive-photoproduction cross sections for all members of an isomultiplet will be equal. For the nonstrange charmed baryons we expect

$$\sigma(C_1^0) = \sigma(C_1^+) = \sigma(C_1^{++}) \tag{11}$$

and

$$\sigma(C_1^{*0}) = \sigma(C_1^{*+}) = \sigma(C_1^{*++}) . \tag{12}$$

If the $c\bar{c}$ component of the current were not dominant, charmed quarks would have to be produced in pairs from the vacuum. The reluctance of charmed particles to be produced in strong interactions argues against the latter process.

Equations (11) and (12) can be checked by comparing the signals for $\bar{C}_0^-\pi^-$ and $\bar{C}_0^-\pi^+$ near 2500 MeV/c^2 in the data of Ref. 6.

Once the $c\bar{c}$ pair has been produced, each quark must dress itself to form a baryon. It is most economical to assume that this dressing takes place by the creation of a diquark-antidiquark pair. The diquarks present in the ground-state baryons have $I = J = 1$ or $I = J = 0$.[22] If any diquark can be produced with equal probability,[23] the inclusive production of $C_0\bar{C}_0$ pairs is $\frac{1}{10}$ of the total rate to produce ground-state pairs.[21] If, moreover, the spins of the charmed quarks and diquarks are uncorrelated, the *inclusive* production rates are[24]

$$C_0 : C_1 : C_1^* = 1:3:6 , \tag{13}$$

up to phase-space corrections. This is precisely the ratio associated with the spin × isospin statistical weights.

We now embrace the spin-counting arguments of Ref. 21 to estimate the relative rates for photoproduction of the two-body final states $\bar{C}_0C_0$, $\bar{C}_1C_1$, $\bar{C}_1C_1^* + C_1\bar{C}_1^*$, and $\bar{C}_1^*C_1^*$. The final $c\bar{c}$ pair is in a state with quark spin 1. The diquark Q and antidiquark $\bar{Q}$ are taken to be produced with total spin $S^2 = (S_Q + S_{\bar{Q}})^2$; for s-wave production $\langle S^2\rangle = 0$, while for d-wave production $\langle S^2\rangle = 6$. The spins of the diquarks and charmed quarks are regarded as uncorrelated. One then obtains[25] for the relative production probabilities

$$\sigma(C_0\bar{C}_0) = 1 , \tag{14}$$

$$\sigma(C_1\bar{C}_1) = \tfrac{1}{3} + \tfrac{1}{6}\langle S^2\rangle , \tag{15}$$

$$\sigma(C_1\bar{C}_1^* + \bar{C}_1C_1^*) = \tfrac{16}{3} - \tfrac{1}{3}\langle S^2\rangle , \tag{16}$$

$$\sigma(C_1^*\bar{C}_1^*) = \tfrac{10}{3} + \tfrac{1}{6}\langle S^2\rangle . \tag{17}$$

When $\langle S^2\rangle = 0$, we recover the relative rates 3:1:16:10 of Ref. 21. Equations (13)–(17) refer to sums over the charge states of C_1 and C_1^*.

Even substantial d-wave production, however, does not vitiate the conclusion that (16) and (17) should be the dominant processes not far above threshold. As the energy increases, the $c\bar{c}$-dominance hypothesis becomes less appealing and Eqs. (13)–(17) should no longer be valid.

The inclusive result (13) has an important application to the photoproduction data of Ref. 6. The $\bar{C}_0^-$ signal appears to form a state of higher mass when combined with a π^- or a π^+. Let us assume that both $\bar{C}_1$ and $\bar{C}_1^*$ decay strongly into $\pi\bar{C}_0$. Then the observed $\bar{C}_0^-$ signal has the following origins:

10% produced directly ,

10% from the sequential decay $\bar{C}_1^{--} \to \pi^-\bar{C}_0^-$,

10% from the sequential decay $\bar{C}_1^{-} \to \pi^0\bar{C}_0^-$,

10% from the sequential decay $\bar{C}_1^{0} \to \pi^+\bar{C}_0^-$,

20% from the sequential decay $\bar{C}_1^{*--} \to \pi^-\bar{C}_0^-$,

20% from the sequential decay $\bar{C}_1^{*-} \to \pi^0\bar{C}_0^-$,

20% from the sequential decay $\bar{C}_1^{*0} \to \pi^+\bar{C}_0^-$.

Thus, the ratios of signals giving rise to $\overline{C}_0^-$ will include, for example,

$$\text{no } \overline{C}_1^{--} \text{ or } \overline{C}_1^{*--}:\overline{C}_1^{--}:\overline{C}_1^{*--} = 7:1:2\,. \tag{18}$$

Some 40% of the $\overline{C}_0^-$ observed in Ref. 6 *will not contribute* to the $\pi^{\pm}\overline{C}_0^-$ peaks near 2500 MeV/c^2. We shall discuss the 30% which do contribute to each 2500-MeV/c^2 peak in more detail after reviewing expectations for the masses of charmed baryons.

IV. PROPERTIES OF C_1 AND C_1^*

A. Charmed-baryon masses

The mass splittings among C_0, C_1, and C_1^* were estimated well in advance of any data on the basis of a quark-gluon model.[26] We present here an abbreviated derivation of the relevant mass formulas, in order to persuade the reader (and ourselves) that there is no plausible theoretical alternative to these splittings.

The Λ, Σ, and Y_1^* may be viewed for our purposes as s-wave composites of a strange quark and a nonstrange diquark. Two circumstances act to split the masses. First, the nonstrange diquark Q_0 in the Λ has $I=J=0$, while the diquark Q_1 in the Σ and Y_1^* has $I=J=1$. These two diquarks can have different masses. Secondly, the diquark Q_1 can be coupled with the strange quark to a state of total spin $\frac{1}{2}$ (the Σ) or spin $\frac{3}{2}$ (the Y_1^*). The hyperfine interaction due to gluon exchange, proportional to $(m_{Q_1}m_s)^{-1}$, will split these two states from one another. Similar considerations apply to the C_0, C_1, and C_1^* system, with the strange quark replaced by the charmed one. The ratio of charmed-quark mass m_c to strange-quark mass m_s can be obtained by comparing the hyperfine splittings between D^* and D with those between K^* and K.[26]

From these considerations, we obtain the following mass formulas:

$$\begin{aligned} M(C_1^*) - M(C_1) &= \frac{m_s}{m_c}\,[M(Y_1^*) - M(\Sigma)] \\ &= \frac{M(D^*) - M(D)}{M(K^*) - M(K)}\,[M(Y_1^*) - M(\Sigma)] \\ &\simeq 60 \text{ to } 70 \text{ MeV}/c^2\,, \end{aligned} \tag{19}$$

where the range expresses our uncertainty over the D-D^* splitting,[27] and

$$\begin{aligned} \frac{2M(C_1^*)+M(C_1)}{3} - M(C_0) &= \frac{2M(Y_1^*)+M(\Sigma)}{3} - M(\Lambda) \\ &= 206 \text{ MeV}/c^2\,. \end{aligned} \tag{20}$$

The combinations of isovector states in (20) are those for which $\langle \vec{S}_{Q_1}\cdot\vec{S}_c\rangle = 0$ and $\langle \vec{S}_{Q_1}\cdot\vec{S}_s\rangle = 0$. These relations assume that the radii of charmed and strange particles are similar.

If the geometrical size of the charmed particles is smaller than that of the strange ones, the splittings (20) will be somewhat larger for the charmed particles. We expect, however, that size effects will largely cancel in Eq. (19). An important consequence of (19) and (20) is the prediction that *both C_1 and C_1^* should be able to decay into πC_0.*[26] Using $M(C_0) = 2250$ MeV/c^2, we compute

$$M(C_1) = 2409\text{–}2416 \text{ MeV}/c^2\,, \tag{21}$$

$$M(C_1^*) = 2476\text{–}2479 \text{ MeV}/c^2\,. \tag{22}$$

With fine enough resolution, both the states in (21) and (22) should appear as $\pi^-\overline{C}_0^-$ resonances in the data of Ref. 6. The areas under the C_1 and C_1^* peaks should be in the ratio $\frac{1}{2}$, according to Eq. (18). We shall return shortly to predictions of their widths. If the experimental resolution is too coarse to resolve C_1 from C_1^* in the πC_0 channel, Eqs. (18) and (20) imply that the observed peak should be centered at $2250+206=2456$ MeV/c^2. As already remarked, a slightly higher value cannot be excluded if the charmed-baryon radius is smaller than that of the strange baryons. The peak suggested[6] near 2500 MeV/c^2 invites identification with the C_1-C_1^* complex.

B. Strong-decay widths

The widths of C_1 and C_1^* can be estimated on the basis of the single-quark-transition scheme motivated by the Melosh transformation.[28] The calculations are straightforward, and the use of partial conservation of axial-vector current (PCAC) entails very definite kinematic factors,[29] which will be subjected to stringent tests by the charmed-baryon widths.

First one has the relation[30]

$$\frac{\Gamma(C_1\to C_0\pi)}{\Gamma(C_1^*\to C_0\pi)} = \left(\frac{p}{p^*}\right)\left(\frac{p_0}{p_0^*}\right)^2 \simeq \frac{1}{4}\,, \tag{23}$$

where p and p^* are the c.m. momenta for $C_1\to C_0\pi$ and $C_1^*\to C_0\pi$, respectively, and p_0 and p_0^* are the corresponding quantities for massless pions. The ratio in Eq. (23) would be $\frac{1}{10}$ if the conventional p-wave barrier factor $(p/p^*)^3$ were used. In the limit of equal phase space the two rates would be identical. For these $L=0$ to $L=0$ transitions, pion emission occurs when the diquark Q_1 has helicity zero. This configuration is equally probable in the spin-averaged C_1 and C_1^* states.

To estimate the rate for $C_1^*\to C_0\pi$ we note that it is entirely analogous to the decay $Y_1^*\to\Lambda\pi$ with the charmed quark replacing the strange one. Then, in notation as above, we have the ratio

$$\frac{\Gamma(C_1^* \to C_0\pi)}{\Gamma(Y_1^* \to \Lambda\pi)} = \left(\frac{p^*}{p^\Lambda}\right)\left(\frac{p_0^*}{p_0^\Lambda}\right)^2 \simeq 0.66\,, \tag{24}$$

which implies

$$\Gamma(C_1^* \to C_0\pi) = 20 \text{ MeV} \tag{25}$$

and, by virtue of (23),

$$\Gamma(C_1 \to C_0\pi) = 4.8 \text{ MeV}. \tag{26}$$

Once again, the prediction (24) provides a stringent test of the kinematic factors associated with the use of PCAC. More naive approaches[31] would predict

$$\frac{\Gamma(C_1^* \to C_0\pi)}{\Gamma(Y_1^* \to \Lambda\pi)} = \left(\frac{p^*}{p^\Lambda}\right)^3\left(\frac{M(Y_1^*)}{M(C_1^*)}\right)^2 \simeq 0.18 \tag{27}$$

and hence $\Gamma(C_1^* \to C_0\pi) \simeq 5.4$ MeV and $\Gamma(C_1 \to C_0\pi) \simeq 0.5$ MeV.

C. Details of the $C_0\pi$ spectrum

The predictions for production cross sections, masses, and widths indicate that the $\bar{C}_0^-\pi^\pm$ spectrum observable in the experiment of Ref. 6 will have very interesting structure. The expected spectrum is shown in Fig. 7. The solid curve is the theoretical expectation of a two-peak structure with twice as many events in the broad C_1^* peak as in the narrow C_1 peak. The histogram shows the prediction after smearing with a Gaussian resolution with $\sigma = 15$ MeV. Resolution of the two peaks would be an important advance in charmed-baryon spectroscopy.

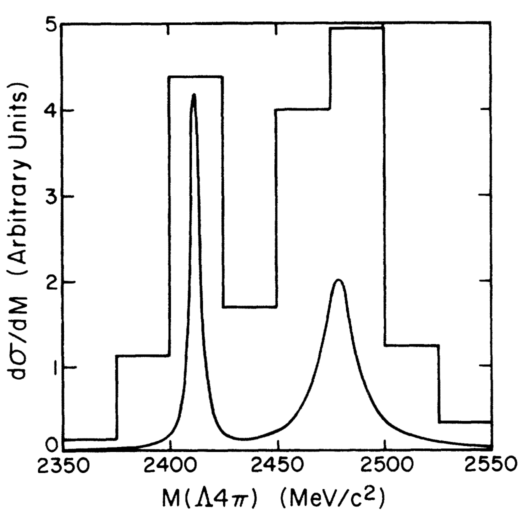

FIG. 7. Effective-mass spectrum of $\Lambda 4\pi$ for the photoproduction of C_1 and C_1^* and the sequential decay $C_1^{(*)} \to \pi C_0$, $C_0 \to \Lambda 3\pi$. The smooth curve is the theoretical prediction. The histogram is the result of smearing with a Gaussian resolution function of width 15 MeV/c^2 and binning in 25-MeV/c^2 bins.

V. SPIN-PARITY ASSIGNMENTS

So long as two-body decay channels are observed, the classical methods of baryon spectroscopy[32] are applicable to the new charm candidates. If the transition $C_0^+ \to \Lambda\pi^+$ is a weak decay, we expect it to be analogous to[33] $\Xi^- \to \Lambda\pi^-$. For an unpolarized sample of spin-$\frac{1}{2}$ C_0's the decay angular distribution will be isotropic, if the Λ polarization goes unobserved. Observing the Λ helicity by its self-analyzing decay, we may measure the interference between s-wave and p-wave decay amplitudes which is characterized by the parameter α in

$$W_{\frac{1}{2}}(\theta) = \tfrac{1}{2}(1 - \alpha P_\Lambda \cos\theta)\,, \tag{28}$$

where θ is the polar angle of the Λ momentum in the helicity frame of the C_0. Once the C_0 is established as spin-$\frac{1}{2}$, an isotropic distribution of $C_1 \to C_0\pi$ is necessary (but not sufficient) to establish C_1 as spin-$\frac{1}{2}$. If the spin of C_1^* is $\frac{3}{2}$ (and that of C_0 is $\frac{1}{2}$) then the decay angular distribution for $C_1^* \to C_0\pi$, averaged over azimuth, must have the form

$$W_{3/2}(\theta) = \tfrac{1}{4}(1 + 4\rho_{33}) + \tfrac{3}{4}(1 - 4\rho_{33})\cos^2\theta\,. \tag{29}$$

More generally, for any decay of the form spin-J baryon $\to$ spin-$\frac{1}{2}$ baryon + pseudoscalar, if the decay angular distribution is of degree $2n$ in $\cos\theta$, then $J \geq n + \frac{1}{2}$. If the observed distribution is quadratic, it may be possible to rule out spins higher than $\frac{3}{2}$ by means of a simple test.[34] Assume that the observed distribution is

$$W(\theta) = a + b\cos^2\theta\,. \tag{30}$$

Then (for $J > \frac{1}{2}$) the ratio of the coefficients b/a is restricted to the range

$$-1 \leq \frac{b}{a} \leq \frac{2J+3}{2J-1} \leq 3\,. \tag{31}$$

Thus an observed anisotropy in the range

$$2 < b/a \leq 3$$

implies $J = \frac{3}{2}$, one in the range

$$\tfrac{5}{3} < b/a \leq 2$$

implies $J \leq \frac{5}{2}$, one in the range

$$\tfrac{3}{2} < b/a \leq \tfrac{5}{3}$$

implies $J \leq \frac{7}{2}$, etc. If the observed value lies in the range (for $b \neq 0$)

$$-1 \leq b/a \leq 1$$

it can only be inferred that $J > \frac{1}{2}$.

VI. CHARACTERISTICS OF OTHER CHARMED BARYONS

We conclude with a brief discussion of the prospects for producing other charmed baryons:

those with $C=1$, $S=-1$ and those with $C=1$, $S=-2$. We refer to Tables I and II for a summary of their properties. The favored decay channels have been discussed in Table IV and Figs. 5 and 6.

The production of pairs of these more exotic charmed baryons may be estimated along the lines of the discussion leading to (13)–(17). Assuming as a rough approximation that all uncharmed diquarks are equally difficult to produce, we obtain the inclusive ratios

$$C_0:C_1:C_1^*:A:S:S^*:T:T^* = 1:3:6:2:2:4:1:2\,. \qquad (32)$$

Straightforward mass estimates[35] indicate that $S(2560)$ and $S^*(2610)$ will decay by strong or electromagnetic cascade to $A(2470)$ and that $T^*(2770)$ will cascade to $T(2730)$. Hence for the detection of the weakly decaying states the observed ratio should be

$$C_0:A:T = 10:8:3\,. \qquad (33)$$

Thus the charmed-strange states $A^{+,0}$ may be photoproduced nearly as copiously as C_0^+.

There is one aspect wherein e^+e^- annihilation may be somewhat more efficient than photoproduction in the production of charmed-baryon pairs.[36] If the photoproduction of charmed-baryon pairs must be initiated by a strong interaction between the target and one of the charmed quarks into which the photon has dissociated, the diffractive dissociation of the photon into charmed-particle pairs may be considerably suppressed in comparison with the corresponding e^+e^- process. The observation of Ref. 6 indicates that whatever the degree of this suppression it can be overcome in practice.

VII. SUMMARY

We have used the observation of a candidate for C_0^+, the lowest-lying charmed baryon, to sharpen and extend predictions of the charm model and to help refine some ideas about particle spectroscopy. We have introduced a simply way for depicting multibody decays such as $C_0 \to \Lambda 3\pi$ in a maximally coplanar way. The current-algebra prediction that the odd pion in the $\Lambda 3\pi$ decay cannot be soft can be tested in the near future.

We have estimated multiplicities for the decays $C_0 \to \Lambda + m\pi(\langle m\rangle \simeq 2.8)$, $C_0 \to \Sigma + m\pi(\langle m\rangle \simeq 2.7)$, $C_0 \to \bar{K}N + m\pi(\langle m\rangle \simeq 1.5)$, and others. Prominent charged modes, as yet undetected, should be $C_0^+ \to \Lambda\pi^+$, $\Sigma^\pm\pi^\mp\pi^\pm$, and $K_S p$.

On the basis of estimated production rates, mass splittings, and strong-decay widths, we have made the suggestion that the $C_0\pi$ system should be seen to have two peaks, a narrow one around 2.41 GeV/c^2 and a wider one around 2.48 GeV/c^2, whose areas are in the ratio 1:2. Finally, we have discussed the possible production of still other charmed baryons, and conclude that the $A^0, A^+ = c[sd], c[su]$ doublet has a good chance of being seen in the near future.

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limited to an unknown extent by the Λ-Σ mass splitting.

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[23]It appears likely that the isoscalar diquark Q_0 is lighter than the isovector diquark Q_1 and thus easier to create in pairs. If the relative creation probability is $P(Q_0)/P(Q_1)=r$, $C_0\bar{C}_0$ pairs will make up a fraction $r/(9+r)$ of the total.

[24]The unit weight is replaced by r under the assumptions of footnote 23.

[25]Under the more general assumptions of footnote 23, the right-hand side of (14) is multiplied by $r/(9+r)$; the right-hand sides of (15)–(17) are multiplied by $1/(9+r)$.

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[27]We assume $M(D^*)=2.01\pm 0.02$ GeV/c^2 and $M(D)=1.87$ GeV/c^2, in accord with the observations of Ref. 3.

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[36]We thank D. Horn for a discussion of this possibility.