WEAK DECAYS OF THE CHARMED BARYON C_0^+ AND THE INCLUSIVE YIELD OF Λ AND p

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We calculate the decay rates of the charmed baryon state $C_0^+(2.26)$ into 25 two body and quasi two body states involving baryons and mesons with $J^P = \frac{1}{2}^+, \frac{3}{2}^+, 0^-$ and 1^-. These modes yield a width of $\Gamma = 16.3 \times 10^{12}\ \mathrm{s}^{-1}$ and an inclusive yield of $\Lambda/\mathrm{p} \cong 40\%$.

Recently Spear [1] has published evidence that the inclusive production of $\bar{\mathrm{p}}$ and Λ (or $\bar{\Lambda}$) in e^+e^--annihilation increases when one passes through the expected threshold for charmed baryon pair production at $\sqrt{s} \cong 4.5$ GeV. This may be the long awaited signal of charmed baryon pair production in e^+e^--annihilation, although the small yield of additional Λ's (or $\bar{\Lambda}$'s) compared to additional $\bar{\mathrm{p}}$'s is somewhat puzzling.

According to the charmonium picture the only stable charmed baryon state made from a c-quark and u,d-quarks is the C_0^+ which has been identified in a photoproduction [2] and a neutrino production [3] experiment. The mass of the C_0^+ has been given at 2.26 GeV. The next stable charmed baryon with an s-quark added is the doublet $A^{+,0}$ = (csu(d)) with an expected mass at around $\simeq 2.5$ GeV [4]. Thus any new baryon production in the region $4.5 \lesssim \sqrt{s} < 5$ GeV is expected to be the debris of weakly decaying C_0^+'s. Therefore it seems to be worthwhile to try and estimate branching fractions of the decay of the C_0^+.

In this paper we take the point of view that the C_0^+ decays into two body and quasi two body states most of the time. This is orthogonal to a statistical description of this decay [4,5] in which the multiple mesons originating from the C_0^+ are essentially uncorrelated except for possible jet configurations. The latter approach already seems to be at variance with some of the observed D-decay modes [6]. On the other hand the evidence for resonance dominance of multibody final states in most production processes has become mounting in the last few years.

If one considers the Cabibbo favoured decays of the C_0^+ into ground state baryons and mesons one counts 28 possible decay channels of which 3 cannot be reached if the mass of the C_0^+ is 2.26 GeV. The bulk of the C_0^+ decay should be made from these channels. Higher resonance contributions are likely to be suppressed because of phase space. Also the Cabibbo suppressed decays to the lowlying baryons and mesons are not likely to be important due to the Cabibbo suppression factor $\mathrm{tg}^2\theta \cong 5\%$, even though their phase space is somewhat larger than that of the Cabibbo favoured decays. In QCD the basic effective $\Delta C = 1$ transition operator can be obtained from the short distance behaviour of the current–current product of *charged* currents [7] and is given by (see e.g. [8])

$$\mathcal{H}_W = \frac{G}{\sqrt{2}}\cos^2\theta_c\left[\frac{f_+ + f_-}{2}(\bar{u}^i\gamma_\mu(1-i\gamma_5)d_i)(\bar{s}^j\gamma^\mu(1-i\gamma_5)c_j) + \frac{f_+ - f_-}{2}(\bar{s}^i\gamma_\mu(1-i\gamma_5)d_i)(\bar{u}^j\gamma^\mu(1-i\gamma_5)c_j)\right], \quad (1)$$

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where the i and j are colour indices which are summed over.

The coefficients $f_\pm$ embody the renormalization effects due to hard gluon exchange. These have been estimated in ref. [8] (see also ref. [12]) and take the values

$$f_- \cong 2.15\,, \qquad f_+ \cong 0.68\,. \tag{2}$$

With the help of the effective hamiltonian eq. (1) one can immediately estimate the contributions of the factorizable diagrams Ia and Ib of fig. 1 that involve two inactive spectator quarks. The calculation proceeds in complete analogy to the evaluation of D- and F-meson decay amplitudes as performed in refs. [8,9]. However, one should already now keep in mind that these contributions are likely to constitute only a fraction of the total amplitude, which receives contributions also from diagrams of type II and III in fig. 1. This is different in the mesonic case where the factorizing contributions determine the whole amplitude. We shall return to this point later.

In fact one can easily convince oneself that of the possible 28 ground state decay channels the only possible transitions proceeding via the factorizable diagrams Ia and Ib are the decays $C_0^+ \to \Lambda\pi^+(\rho^+)$ and $C_0^+ \to p\overline{K}^o(\overline{K}^{*o})$. Defining our nonleptonic amplitudes as usual by

$$\langle B'(p_2)P(p_3)|\mathcal{H}|B(p_1)\rangle = \bar{u}(p_2)(A + \mathrm{i}B\gamma_5)u(p_1) \tag{3}$$

and by

$$\langle B'(p_2)V(p_3)|\mathcal{H}|B(p_1)\rangle = \bar{u}(p_2)\epsilon_b^*(A_1\gamma_b \mathrm{i}\gamma_5 + A_2 p_{1b}\mathrm{i}\gamma_5 + B_1\gamma_b + B_2 p_{1b})u(p_1)\,, \tag{4}$$

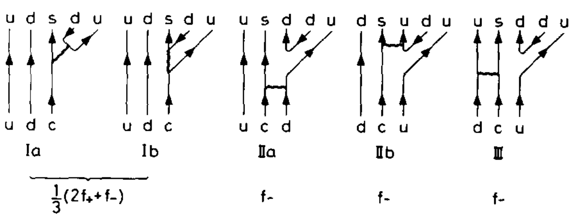

Fig. 1. Quark diagrams for two body decays of C_0^+. Quark lines are labelled for the specific decay $C_0^+ \to \Lambda\pi^+(\rho^+)$. The appropriate short distance factors are given underneath the diagrams. For neutral final state mesons the short distance factor of (Ia + Ib) is $\frac{1}{3}(2f_+ - f_-)$. Diagrams Ia and Ib are related by Fierz crossing and diagrams IIa and IIb by C-conjugation and crossing.

we find for the factorizable contribution (diagrams Ia and Ib in fig. 1) to $C_0^+ \to \Lambda\pi^+(\rho^+)$

$$A = \frac{G}{\sqrt{2}}\chi_+ \cos^2\theta_c f_\pi (M_1 - M_2) H_1^{(3^*)}\,,$$
$$B = \frac{G}{\sqrt{2}}\chi_+ \cos^2\theta_c f_\pi (M_1 + M_2) H_3^{(3^*)}\,, \tag{5a}$$

$$A_1 = \frac{G}{\sqrt{2}}\chi_+ \cos^2\theta_c m_\rho^2 f_{\rho^+} H_3^{(3^*)}\,,$$
$$A_2 = 0\,,$$
$$B_1 = \frac{G}{\sqrt{2}}\chi_+ \cos^2\theta_c m_\rho^2 f_{\rho^+}(H_1^{(3^*)} + H_2^{(3^*)})\,, \tag{5b}$$
$$B_2 = -\frac{G}{\sqrt{2}}\chi_+ \cos\theta_c m_\rho^2 f_{\rho^+}\left(\frac{2}{M_1 + M_2}\right) H_2^{(3^*)}\,.$$

For the decay $C_0^+ \to p\overline{K}^o(\overline{K}^{*o})$ one has to multiply the above amplitudes with the SU(4) Clebsch–Gordan factor $\sqrt{3/2}$ and has to replace $\chi_+ = \frac{1}{3}(2f_+ + f_-)$ by $\chi_- = \frac{1}{3}(2f_+ - f_-)$. Also one replaces f_π by f_K and $m_\rho^2 f_\rho$ by $m_{K^*}^2 f_{K^*}$. The $H_i^{(3^*)}$ are SU(4) reduced matrix elements and can be expressed in terms of the known vector and axial form factors of the nucleon as shown by Buras [10]. Using $f_\pi = 0.932\, m_{\pi^+}$, $f_K = 1.28\, f_\pi$, $f_{\rho^+} = 0.247$, $f_{K^*} = f_{\rho^+}$ and the $H_i^{(3^*)}$ as given by Buras [10] as well as the values for the renormalization coefficients f_+ and f_- as given in eq. (2) one calculates the following rates

$$\Gamma_{C_0^+\to\Lambda\pi^+} = 0.31 \times 10^{12}\ \mathrm{s}^{-1}\,,$$
$$\Gamma_{C_0^+\to\Lambda\rho^+} = 0.94 \times 10^{12}\ \mathrm{s}^{-1}\,,$$
$$\Gamma_{C_0^+\to p\overline{K}^o} = 0.05 \times 10^{12}\ \mathrm{s}^{-1}\,, \tag{6}$$
$$\Gamma_{C_0^+\to p\overline{K}^{*o}} = 0.18 \times 10^{12}\ \mathrm{s}^{-1}\,.$$

We reiterate that these rates are not meant to accurately give the real rates since they have been calculated only from the factorizable part.

Before turning to the calculation of the contributions of the other diagrams in fig. 1 we briefly consider the possibility of obtaining rough estimates of partial rates using SU(4) for those cases where old decays exist. For $C_0^+ \to B(\frac{1}{2}^+) + M(0^-)$ the relevant formula (using $\overline{6}$ (or 20″) dominance for $\mathcal{H}_W$) have been written down in ref. [11]. The results are given in table 1 in brackets. We have assumed SU(4) for the

Table 1
Partial decay rates of C_0^+ into ground state baryons and mesons. Units are [10^{12} s^{-1}]. Numbers in brackets are SU(4) predictions calculated from $\Delta C = 0$ decays.

$\Lambda\pi^+$	$\Sigma^0\pi^+$	$\Sigma^+\pi^0$	$\Sigma^+\eta$	$\Sigma^+\eta'$	$p\overline{K}^0$	Ξ^0K^+
0.077 (0.279)	0.091 (0.050)	0.094 (0.050)	0.095 (0.125)	0.558 –	0.729 (0.627)	0.219 (0.068)
$\Lambda\rho^+$	$\Sigma^0\rho^+$	$\Sigma^+\rho^0$	$\Sigma^+\omega$	$\Sigma^+\varphi$	$p\overline{K}^{*0}$	Ξ^0K^{*+}
0.905	0.684	0.692	1.849	0.060	1.689	0.197
$\Sigma^{*0}\pi^+$	$\Sigma^{*+}\pi^0$	$\Sigma^{*+}\eta$	$\Sigma^{*+}\eta'$	$\Delta^+\overline{K}^0$	$\Delta^{++}K^-$	$\Xi^{*0}K^+$
0.231 (0.287)	0.231 (0.287)	0.322 (0.399)	0 0	0.510 (0.685)	1.543 (2.091)	0.106 (0.122)
$\Sigma^{*0}\rho^+$	$\Sigma^{*+}\rho^0$	$\Sigma^{*+}\omega$	$\Sigma^{*+}\varphi$	$\Delta^+\overline{K}^{*0}$	$\Delta^{++}K^{*-}$	$\Xi^{*0}K^{*+}$
0.297	0.297	0.255	0	1.102	3.454	0

dimensionless quantities A and B in eq. (3), and have scaled the result by the ratio of enhancement factors [12]

$$f_-^{\Delta C=1}/f_-^{\Delta C=0} \cong 2.1/4\,. \tag{7}$$

It is not clear how valid such a procedure is since, for example, the effective current contribution to diagram I has also a piece proportional to f_+ (transforming as 84 in SU(4)). Also the p.v. contribution of diagram I is purely SU(4) breaking (see eq. (5a)) and may be important.

In the case of $C_0^+ \to B(\frac{3}{2}^+) + M(0^-)$ one may attempt to calculate the partial rates in terms of the Ω^- decay rates. There is in fact only one SU(4) invariant describing the 7 new decays $C_0^+ \to B(\frac{3}{2}^+)M(0^-)$ and the old decay $\Omega^- \to \Lambda K^-$ assuming again 20″ dominance ‡1. The partial rate for the latter decay can be very roughly estimated by taking the lifetime and the number of events reported for the 3 possible Ω^- decays published in ref. [13]. One obtains $\Gamma_{\Omega^-\to\Lambda K^-} \cong 0.38 \times 10^{10}$ s^{-1}. Nothing is known about the relative amount of p- and d-wave amplitude in the decay. One can probably safely assume that the d-wave contribution is suppressed or even zero as in our later model calculation (see also ref. [14]). Let us then assume that SU(4) holds for the dimensionless p-wave amplitude $B/(M_1 + M_2)$, where we define

$$\langle B'(p_2)P(p_3)|\mathcal{H}|B(p_1)\rangle = \bar{u}_\alpha(Ap_{1\alpha}i\gamma_5 + Bp_{1\alpha})u\,. \tag{8}$$

After multiplying with the ratio eq. (7) one arrives at the rates given in table 1 in brackets.

Not much can be learned from SU(4) about the decays $C_0^+ \to B(\frac{1}{2}^+) + M(1^-)$ and $C_0^+ \to B(\frac{3}{2}^+) + M(1^-)$. There are too many amplitudes to obtain any useful relations among the various C_0^+ decay channels. It is also impossible to obtain absolute rates since there are no corresponding $\Delta C = 0$ decays that could be used for normalization.

In order to be able to make any progress we therefore propose to use SU(8)-type quark model wave functions for the ground state baryons and mesons to calculate the important C_0^+ decay modes according to the diagrams in fig. 1. The corresponding amplitudes are given by

$$\begin{aligned} T_{B_1\to B_2M} = {} & H_1\overline{B}_2^{ABC'}B_{1ABC}\overline{M}_D^{D'}(O_{C'D'}^{CD} - \tfrac{1}{3}O_{D'C'}^{CD}) \\ & + H_2\{\overline{B}_2^{AB'D}B_{1ABC}\overline{M}_D^{D'}O_{B'D'}^{BC} \\ & + \overline{B}_2^{AB'C'}B_{1ABC}\overline{M}_D^{B}O_{B'C'}^{CD}\} \\ & + H_3\overline{B}_2^{A'B'C'}B_{1ABC}\overline{M}_{C'}^{C}O_{A'B'}^{AB}\,. \end{aligned} \tag{9}$$

‡1 This is easily seen by considering SU(4) couplings in the t-channel where there are two reduced couplings transforming as $\underline{15}$ and $\underline{45}$. The above 8 decays can be seen to decouple from the $\underline{15}$ leaving us with one invariant coupling.

The B_{ABC} and M_A^B denote ground state quark model wave functions.

Each index A stands for a pair of indices (α, a) where α and a denote the spin and flavour degrees of freedom. O_{AB}^{CD} describes the structure of the effective current–current interaction and can be e.g. deduced for $\Delta C = 1$ decays from eq. (1). H_1, H_2 and H_3 are wavefunction overlaps corresponding to the diagrams I, II and III. In eq. (9) we have already summed over colour degrees of freedom. One should note that diagrams II and III contain only contributions from f_- (transforming as 20″) due to the ground state nature of the baryons whereas diagram I obtains contributions from $\chi_+ = \frac{1}{3}(2f_+ + f_-)$ and $\chi_- = \frac{1}{3}(2f_+ - f_-)$ depending on whether one has a charged or a neutral meson in the final state, respectively.

In ref. [14] we have demonstrated that the amplitude eq. (9) accounts quite well for the ordinary $\Delta C = 0$ nonleptonic hyperon decays. This is not difficult to understand since one can show that the various terms in eq. (9) correspond to the various contributions arising in the more conventional current algebra approach as e.g. in the successful description of nonleptonic hyperon decays by Gronau [15]. For example, for the p.v. part, only the contributions proportional to H_1 and H_2 survive. The first term gives rise to the K*-pole contribution, and the second term has the exact structure of the ETC term ‡2 [14]. As one can see from cutting the diagrams I, II and III, one has in the case of the p.c. p-waves amplitudes contributions corresponding to K^0 and baryon poles just as in the current algebra approach. The scale and phase between s- and p-waves was found to be reproduced quite well by the amplitude eq. (9), thus embodying the content of the Goldberger–Treiman relation, which relates the scale and phase between s- and p-waves in the current algebra approach.

The effective paraquark current–current interaction used in ref. [14] corresponds in modern language to the short distance factors $f_- = 1$ and $f_+ = 0$, which gives $\chi_\pm = \pm\frac{1}{3}$. In the case of $\Lambda \to p\pi^-$ we had noted that the fit value for the overlap H_1 was $\simeq 5$ times the value derived from factorization. This enhancement factor is now provided by the short distance expansion of QCD, since, e.g., Ellis et al. find $\chi_+^{\Delta C=0} = \frac{5}{3}$ [12]. For the ratio of overlap functions H_2 and H_3 our best fit values was

$$H_2/H_3 = -0.82 .$$

This ratio is not affected by the short distance effects. However, the absolute values of H_2 and H_3 have to be scaled by the factor $f_-^{\Delta C=1}/f_-^{\Delta C=0}$ in eq. (7) when one is applying the theory to the $\Delta C = 1$ decays.

If one uses the relativistic quark model wave functions of ref. [17] one has to factor off a mass term $(M_1 M_2)^{-1}$ in the factorizable contribution (diagrams Ia and Ib in fig. 1) proportional to H_1, i.e. one has to introduce $\hat{H}_1 = (1/M_1M_2)H_1$ in order to assure correct charge normalization of the baryon current matrix elements. We note in passing that the resulting SU(4) structure of the baryonic current matrix elements does not differ much from the SU(4) structure assumed by Buras [10]. For consistency reasons we also factor the same mass term from the other two contributions, i.e. we write $\hat{H}_i = (1/M_1M_2)H_i$. Also we increase the amplitudes involving vector mesons by the factor 1.46 since the quark model wave functions used in our calculation lead to $f_{\rho_+}/f_\pi(=f_K) = 1/m_\rho$ which is too small by the above factor when compared to experiment.

We have taken the best fit values for $\hat{H}_2$ and $\hat{H}_3$ from ref. [14]. After scaling them according to the factor $f_-^{\Delta C=1}/f_-^{\Delta C=0}$ of eq. (7) all the necessary ingredients for the calculation of diagrams II and III are given ‡3. Using the relativistic quark wave functions of ref. [17] one calculates the relevant amplitudes and then adds them to the factorizable contributions calculated in eq. (6). Finally one arrives at the partial rates given in table 1. The sum of the partial rates appearing in table 1 gives a lower bound for the total rate of hadronic C_0^+ decays. We find

$$\Gamma_{C_0^+ \to \text{ quasi two body}} = 16.29 \times 10^{12}\ \mathrm{s}^{-1} . \qquad (10)$$

As argued before, this rate should already be quite close to the total hadronic rate. The two body modes $C_0^+ \to B(\frac{1}{2}^+) + M(0^-)$ constitute 11% of the above rate. The semileptonic rate (e or μ) of C_0^+ into single ground state baryons has been calculated by Buras to be $0.6 \times 10^{12}\ \mathrm{s}^{-1}$ [10]. The semileptonic branching ratio for decays into ground state baryons is thus 4%. If this number reflects the total semileptonic branching ratio

‡2 This can be seen to hold also for the $\Delta C = 1$ s-wave amplitudes [16].

‡3 Details of this calculation will be given in ref. [16].

of C_0^+ this would mean that the semileptonic branching ratio of charmed baryons is approximately half of that of charmed mesons.

We have calculated the average multiplicities in C_0^+ decays from the numbers in table 1 and find ‡4

$$\langle n_{ch} \rangle = 2.81 , \tag{11}$$

$$\langle n_{all} \rangle = 3.94 . \tag{12}$$

This means that the C_0^+ decays on the average into several particles and should be looked for in multibody final states. Also one expects jet-like configurations since the particles originate mostly from resonances. The average multiplicity $\langle n_{all} \rangle$ is approximately the same as given in the statistical model [4,5] so that measurements of this quantity are not useful to discriminate among these two models.

The total rate in eq. (10) is larger than the rate estimate of Ellis et al. based on the picture of the decay of an effectively free quark, who quote $\simeq (1.5 \text{ to } 2) \times 10^{12}\ \mathrm{s}^{-1}$ for $m_c = 1.5$ GeV and $\simeq (6 \text{ to } 8) \times 10^{12}\ \mathrm{s}^{-1}$ for $m_c = 2$ GeV [12]. Their rate estimate is closer to the numbers given in eq. (6) for the factorizable contributions, which shows that the more complicated quark transitions occurring in diagrams II and III may not be adequately estimated by calculating the decay of a free quark.

As a last point we discuss the inclusive yield of Λ's and p's in C_0^+ decays. Let us define the inclusive ratio

$$\frac{\Gamma_{C_0^+ \to \Lambda + X}}{\Gamma_{C_0^+ \to p + X}} = a . \tag{13}$$

Since one produces a $C_0^+ \bar{C}_0^+$ pair in e^+e^--annihilation one has as decay products the pairs $(p\bar{p})$, $(p\bar{\Lambda})$, $(\bar{p}\Lambda)$ and $(\Lambda\bar{\Lambda})$ which appear with the weights

$$(p\bar{p}) : (p\bar{\Lambda}) : (\bar{p}\Lambda) : (\Lambda\bar{\Lambda}) = 1 : a : a : a^2 . \tag{14}$$

In the recent experiment at Spear the following ratio was measured

$$R_{\bar{p}/\Lambda} = \frac{\sigma_{\Lambda \text{ or } \bar{\Lambda}}}{2\sigma_{\bar{p}}} = \frac{a^2 + 2a}{2(1+a)} ,$$

where we have on the r.h.s. introduced the inclusive ratio of eq. (14). For the ratio a we find from $\Gamma_{p+X} = 9.73 \times 10^{12}\ \mathrm{s}^{-1}$ and $\Gamma_{\Lambda+X} = 3.78 \times 10^{12}\ \mathrm{s}^{-1}$ the value $a = 38.9\%$ which gives $R_{\bar{p}/\Lambda} = 33.4\%$ whereas the authors of ref. [1] quote a number of 10–15% for $R_{\bar{p}/\Lambda}$ below and above charm threshold. We do find a suppression of (Λ or $\bar{\Lambda}$)'s relative to $\bar{p}$'s in C_0^+-decays, however, the suppression is not as big as reported in ref. [1]. If the experimentally observed large suppression of excess (Λ or $\bar{\Lambda}$)'s persists, one may have to look for sources other than C_0^+ for excess baryons. For higher energies obvious candidates would be the $A^{+,o}$ and T^o states with masses at $\simeq$2.5 GeV and 2.75 GeV. For lower energies there still exists the possibility that the C_1^o and C_1^{++} members of the C_1 isotriplet decay weakly, if their mass separation to the C_0^+ is too small for pionic transitions.

‡4 We count K_S^o as two particles and take K_L^o to go undetected.

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