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DILEPTON EVENTS AND SEMILEPTONIC DECAY MODES

OF CHARMED BARYONS*

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ABSTRACT

We estimate the semileptonic decay rates for the Λ_c^+ charmed baryon into final states with two hadrons and a lepton pair. We show that these rates are of magnitude comparable to the semileptonic modes into three particles.

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The simplest semileptonic decays of the charmed baryons lead to a noncharmed baryon and lepton pair, and have been theoretically studied by Buras.¹ In the present paper we wish to call attention to the importance of the four-body semileptonic decays of these particles, where an extra meson is produced together with the baryon and the lepton pair. We show that these B_{l4} decays of the Λ_c^+ particle are expected to be about as frequent as the semileptonic decays into three particles. Since the semileptonic modes as a whole are comparatively important, as indicated by the observed rate of dilepton events, we see that B_{l4} decays may become a source of valuable information on the structure of the weak interaction and of the intervening strong interaction mechanisms.

In experiments with neutrino and antineutrino beams in CERN^2 and in Fermilab^{3,4} search of charmed particles was made through final states containing two charged leptons of opposite charges. The analysis of the observed events show that they are likely to be due to the production and subsequent semileptonic decay of charmed particles. The observed rate of dimuon events gives information on the product of the cross section for charmed particle production times the branching ratio for their semileptonic decays. The observed rate is consistent with the estimated theoretical cross section for charm production if the semileptonic branching ratio is nearly ten percent of the total decay rate. 3 The nonleptonic modes contribute only to the single-muon events, and it is interesting to note that the observed ratio of 1 percent between dimuon and singlemuon events fixes a lower limit of 0.01 for the ratio of semileptonic to nonleptonic modes for charmed particles. For baryons these values (the estimated 0.1 and the lower limit 0.01) may be considered as remarkably high, if we recall that for the usual hyperons the corresponding ratio is in no case larger than 10^{-3} . Or, conversely, we can say that in the decays of the usual hyperons

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the ratio is peculiarly low, due to a strong dynamical enhancement favoring the nonleptonic modes.

The rate of dimuon production by antineutrinos is likely to be smaller than the corresponding rate by neutrinos.^{3,5} The quoted observed value³ for the ratio is

$$\frac{\sigma(\bar{\nu} \to 2\mu)}{\sigma(\nu \to 2\mu)} = 0.2 \pm 0.6 \tag{1}$$

which refers to integrated incident neutrino and antineutrino energies. We can expect that for the smaller incident energies this ratio is significantly smaller than one. In fact the thresholds for dimuon events through charmed particle production are different for neutrino and antineutrino beams. The lowest energy for which the charmed particle interpretation of the dimuon events applies corresponds to the simple case in which no extra hadrons are produced in the hadron vertex and the charmed particle is the baryon Λ_c^+ . Then $\nu_{\mu} n \rightarrow \mu^- \Lambda_c^+$ goes, while charm production by antineutrinos requires extra hadrons, and higher energies. Thus the decreasing value of the ratio in Eq. (1) as the beam energies decrease may be an indication of the importance of the mechanism of charmed baryon production in the dilepton events.

No detailed analysis is available for those dilepton events, but they clearly show the importance of the semileptonic decays of charmed particles. It seems to us particularly important the experimental study of dilepton events with neutrino beams of lower energies, so as to minimize the hadronic complications.

A dilepton event of simple structure has been seen⁶ in a neutrino experiment producing μ^-e^+ pairs and associated K_s^o particles, namely

$$\nu_{\mu} N \rightarrow \mu^{-} e^{+} K_{s}^{0} + (neutrals)$$
 (2)

Fourteen such events leading to $\mu^- e^+ K_s^0$ were seen in this experiment, with varied number of hadrons, charged and neutrals, observed in the final state. In two other events a V^0 is seen associated with a $\mu^- e^+$ pair, but the V^0 has not been identified and can either be a K_s^0 or a Λ . Certainly some of these events are due to charmed meson production, but with the results of the calculation of semileptonic decays of charmed baryons into four particles which are here presented, we wish to call attention to the fact that the small number, or the absence, of Λ particles in the final state does not show that a charmed baryon has not been produced. In fact, the four-body decays of Λ_c^+ in general does not give origin to Λ 's and an event such as the one in Eq. (2) may be easily explained in terms of the diagram in Fig. 1.

The B₀₄ Processes

According to the G.I.M. scheme⁷ the $J^{P} = 1/2^{+}$ baryons belong to a SU(4) 20-plet, containing the eight usual baryons, plus nine baryons with charm quantum number C=1, and a triplet of C=2 baryons. The nine charm one states occupy a $\{3^*\}$ and a $\{6\}$ representations of SU(3). The lightest charmed baryon $\Lambda_c^+ = C_0^+ (J^P = 1/2^+, I=0, S=0, C=1, \{3^*\})$ has a quark structure c [ud], where the brackets represent the antisymmetric combination. No other stable charmed baryons have been discovered, and it may well happen that Λ_c^+ will be the only specimen available for the study of the weak decays of charmed baryons.

In terms of quarks the hadronic charged weak current in the G.I.M. model reads

$$\chi_{\rm b} = \cos\theta \; (\bar{\rm ud} + \bar{\rm cs}) + \sin\theta \; (\bar{\rm us} - \bar{\rm cd}) \tag{3}$$

in a simplified notation where the space-time structure (V, A) has been omitted. The charm changing currents satisfy the selection rules $\Delta C = \Delta S$, $\Delta I=0$ in the Cabibbo favored part, and $\Delta C=1$, $\Delta S=0$, $\Delta I=1/2$ in the Cabibbo unfavored term. Thus the semileptonic decays of Λ_c^+ lead to a hadron system with total strangeness -1 and isospin 0 in the favored case and to a system with S=0 and total isospin 1/2 through the sin θ contribution.

The B_{l4} decays of Λ_c^+ which are expected to be most frequent are those with most phase space available. These are

$$\Lambda_{c}^{+} \rightarrow (N\bar{K})^{\circ} \ell^{+} \nu$$

$$\rightarrow (\Sigma \pi)^{\circ} \ell^{+} \nu$$
(4)

for the Cabibbo favored, and

$$\Lambda_{c}^{+} \to (N\pi)^{o} \ell^{+} \nu$$
⁽⁵⁾

for the unfavored processes. Our calculations are limited to these cases.

The physical lowest one particle states most easily available for the hadron system in Cabibbo favored decays of Λ_c^+ are $J^P = 1/2^+ [\Lambda(1115)]$, $J^P = 1/2^- [\Lambda(1405)]$ and $\Lambda(1670)$], $J^P = 3/2^- [\Lambda(1520)]$ and $\Lambda(1690)$], and $J^P = 3/2^+ [\Lambda(1860)]$. For the Cabibbo unfavored decays the dominating states can be $J^P = 1/2^+ [N(939), N(1470)]$ and N(1780)], $J^P = 1/2^- [N(1535)]$ and N(1700)], $J^P = 3/2^- [N(1520)]$ and $J^P = 3/2^+$ [N(1810)]. These states determine the presence of poles close to the region of energy values available for the final state hadrons, and dominate the whole behavior of the amplitudes. The most important contributions to $B_{\ell 4}$ decays leading to a pseudoscalar meson and a baryon in the final state come from the lowest lying $J^P = 1/2^-$ states, namely $\Lambda(1405)$ and N(1535) respectively for the Cabibbo favored and unfavored transitions.

The method of calculation which comes first to one's mind to evaluate a process in which an extra pseudoscalar meson is produced is the current algebra soft meson technique. We do not expect this method to be quantitatively reliable in our case, due to the proximity of the singularities in the amplitudes which we have just mentioned. We can here mention the results of calculations made in the semileptonic decays of Σ hyperons into $N \pi l \nu$, where it has been shown⁸ that the correction to the current algebra calculation due to the presence of the P33 resonance is several times more important than the current algebra result itself.

The pole contributions to the $B_{\ell4}$ processes in Eqs. (4), (5) can be evaluated factorizing the weak vertex and treating the strong interaction through the effective Yukawa couplings between the intermediate baryon states (which are treated as unstable particles, with complex mass) and the final particles.

Born diagrams can also be drawn with charmed particles in intermediate states, in which cases the strong interaction vertex connects the Λ_c^+ baryon line to a charmed baryon (Σ_c , S) and a meson (π , K) or to a charmed meson (D, F) and a baryon (N, Σ). Our calculations have shown that their contributions are very small. We have then concentrated on the evaluation of the contributions coming from the diagrams shown in Fig. 2.

The results of calculations for the dominating contributions from the $J^P = 1/2^-$ intermediate states are shown in Table I. Unfortunately the strong Yukawa coupling of $\Lambda(1405)$ to the $\overline{K}N$ system is only rather poorly known, and our calculations are made for a central value $G^2_{Y_0^*N\overline{K}}/4\pi = .84$ reported⁹ for this quantity.

In the weak vertices we assume a V-A interaction, neglecting other (magnetic, scalar, pseudoscalar and tensor) form factors, and take for the form factors in both vector and axial vector parts a (charmed) vector meson dominance form

$$G^{V, A}(s_2) = (G/\sqrt{2}) / \left[1 - s_2 / m_a^2\right]^2$$
 (6)

where m_a has taken values equal to and above 2 GeV. s_2 is the square of the four-momentum transfer in the weak vertex. This parametrization of the form factors is the same as used by Buras¹ in the study of the three-body semileptonic decay of charmed baryons. We assume for G the value of the Fermi coupling constant $G = 10^{-5}/m_p^2$.

Our point in evaluating the Cabibbo unfavored processes is due to the hope that the larger phase space available for these processes could compensate significantly the effect of the $\sin^2 \theta$ factor. The numbers in Table I show that this is not the case.

In Table I we compare the rates of four-body and three-body modes. In the four-body case several charge states are possible $(\overline{K}^{O}n, K^{-}p, \pi^{+}\Sigma^{-}, \pi^{O}\Sigma^{O}, \pi^{-}\Sigma^{+})$ and we give also the sum of all these rates. We see that decays into four particles can be expected to be as frequent as three-body decays.

An interesting point to note is that the introduction of other form factors in the weak vertices as made by Buras¹ raises the calculated rate of semileptonic decays into three particles by a factor three. This remarkable increase in the calculated value could also be obtained in the cases of decays into four particles, but the present knowledge of the weak vertex connecting Λ_c^+ to $\Lambda(1405)$ is not good enough to justify a more sophisticated calculation.

In the analysis of the final states observed in the dilepton events, the mass invariants for four particles (two of which are the lepton pair) must be constructed, so as to include the important possibility of decays into four particles here discussed. Of course decays into five and more particles can also occur, but their rates should be small as the phase space restrictions are very strong.

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TABLE I

Calculated values for some four-body semileptonic decay modes of the charmed baryon Λ_c^+ in units of 10¹¹ sec⁻¹. The two numbers given in each case for the Cabibbo unfavored case are due to the indetermination of the sign of the coupling of N(1535) and N(1700) to N π . For comparison we show also the rates for the semileptonic decays into three particles.

<u>,</u> +		Vector meson mass m_a in form factors, Eq. (6)			
[∧] c→		2 GeV	2.5 GeV	3 GeV	∞
(Σπ) ^Ο	$e^+\nu$.53	.47	.44	. 39
$(\Sigma \pi)^{O}$	$\mu^+\nu^-$.50	.44	.41	. 35
(NK)	o + e v	. 12	.11	. 10	.090
(NK)	ο μ ⁺ ν	. 10	.093	. 088	.078
Tota	$1 B_{e4}$. 65	.58	.54	.48
Tota	1 B _{µ4}	.60	.53	.50	.43
Λ	$e^{\dagger}\nu$	1.1	. 96	.88	. 75
Λ	$\mu^+ \nu$	1.1	. 93	.85	. 71
$(\pi N)^{\circ}$	$e^{+}\nu$.018033	.015023	.014026	.012022

FIGURE CAPTIONS

- 1. Neutrino induced production of charmed baryon, followed by decay of the baryon into four particles.
- 2. Born diagrams for the calculation of the B_{l4} decays of the charmed baryon. Λ^a and N^a are the I=0 and I=1/2 isobars mentioned in the text.

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Fig. 2