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Λ_c^+ LIFETIME IN A QUARK-DIQUARK SCHEME

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ABSTRACT

The Λ_c^+ lifetime is calculated in a quark-diquark philosophy using previous results and a number of "natural" assumptions. It is shown that the contribution from W-exchange dominates in this case that from W-radiation which is estimated of the order of $\sim 20\%$. The result is in good agreement with the experimental findings.

Key-words: Diquark; Charmed particles; Λ_c^+ decay.

The decay of charmed particles is usually credited to proceed via two main mechanisms: W exchange and W radiation. The former is, in principle, suppressed by helicity conservation in the decay of charmed mesons. On the other hand, if one assumes, as it is customary, that the light quark does not play an important role in the decay (i.e., plays the role of "spectator"), the life times of all charmed mesons should be the same. This is contradicted by the experimental indications

$$(\tau(D^+)/\tau(D^0) \simeq 2\text{-}3\ ,\quad \tau(D^+)/\tau(F^+) \simeq 3\text{-}4)$$

and various models have been suggested to explain this difference between the data and the theoretical expectations[1].

Within the quark-diquark model of baryons which has proven so successful in the spectroscopy of hadrons[2], the suppression of the W-exchange contribution to the decay is not expected to be relevant since we have, in this case, a spin 1 diquark component in the (c d) system (we discard the contribution from the (c u) system which is Cabibbo suppressed). The direct evaluation of this contribution which is the only mechanism which can explain the experimental finding[3] of $\Lambda_c^+ \to \Delta^{++}K^-$, however, is made difficult by several factors such as:

i) the detailed dynamics of the bound state problem, ii) the definition of the probability that the c, d quarks be at a distance within the range of weak interactions etc. To overcome these difficulties, Barger et al.[4] treat the quarks as free particles and use the square of the wave function at the origin (taking it proportional to the mass difference between the Σ_c^+ and the Λ_c^+ within the DGG model[5]) as the probability that the two quarks c and d be within the range of weak interactions.

We take a different and more pragmatic point of view. First we follow the philosophy of the quark-diquark model discussed in ref. 2 to estimate the W-exchange contribution to the Λ_c^+ lifetime using the decay properties of the axial vector (cd) diquark derived previously[6]. Next we correct this result to take into account the W-radiation contribution which dominates the decay of the charmed mesons D^+. The result is in good agreement with the data[7] and proves that W-exchange is, indeed, the dominant mechanism in Λ_c^+ decay.

The effective weak Hamiltonian for the process can be written as[8]

$$H = \frac{G}{\sqrt{2}} \left[c_+ O_+ + c_- O_-\right] \cos^2\theta_C \tag{1}$$

where G is the weak interaction's coupling constant, and

$$O_\pm = \frac{1}{2} \left[(\bar{s}c)(\bar{u}d) \pm (\bar{u}d)(\bar{s}d)\right] \tag{2}$$

where the short-writing

$$(qq') = q_a \gamma_\mu (1-\gamma_5) q'_a \tag{3}$$

is used (a is a color index) and θ_C is the usual Cabibbo angle ($\cos\theta_C \simeq 0.97$).

The coefficients c_+ and c_- containing the leading QCD corrections are estimated[4] to be $c_+ \simeq 0.69$ and $c_- \simeq 2.09$. However, in our present problem, due to the antisymmetry of the baryonic wave function, the term proportional to c_+ does not contribute since it is symmetric for color indices exchange. Hence, the decay width of the Λ_c^+ is proportional to c_-[9].

To write down the Λ_c^+ decay amplitude we shall take a short-cut by making two physically plausible assumptions. They are both in the spirit that motivates the diquark approach.

First of all, we assume that the W-exchange contribution to the decay occurs inside the diquark (cd) i.e., the exchange of a W between the quarks c and d takes place only when they form a diquark. Secondly, we assume that the Λ_c^+ decay via W-exchange is the same that gives rise to the (cd)-diquark decay. The latter hypothesis has the same basis as in the evaluation of the contribution due to W-radiation where the charmed quark is considered free due to the large mass difference with the light (spectator) quark[1].

With the above two assumptions, the Λ_c^+ decay amplitude will be proportional to the probability of forming a diquark (cd) times its decay width

$$\Gamma^{WE}(\Lambda_c^+) = c_-^2 \, P_{D(cd)} \, \Gamma^{WE}(D(cd)) \cos^2\theta_C \tag{4}$$

A priori, one should have two contributions owing to the possibilities that the diquark be in a spin zero (scalar) or in a spin one (axial-vector) configuration. The former, however, can be neglected compared to the latter because, as in the case of pseudoscalar mesons, W-exchange in scalar diquark decay is suppressed by helicity conservation. Furthermore, recent estimates show that the vector diquark decay constants[6] are sizeably larger than the scalar diquark ones[10]. On the other hand, it was argued long ago[11] that the dominant configuration of the charmed baryon Λ_c^+ in a quark-diquark picture is when the quarks c and d form a spin 1 diquark. We shall then retain only the axial vector diquark contribution.

In order to write down the axial-vector diquark decay amplitude, we shall follow the philosophy of ref. 2. In this approach, diquarks are considered as two-quark bound states and the dynamics of the problem goes via a spin dependent relativistic equation[12] with a QCD inspired confining potential. The parameters are fixed from fitting the meson spectroscopy and the diquarks masses are then calculated. The only difference is in the color factors (which affect the effective coupling constant of the problem); thus, while the mesons are in the singlet representation of color SU(3), the diquarks are in the 3 representation and are then used to build up the baryons as quark-diquark bound states[2].

The above analogy between vector mesons and axial diquarks allows us now to write down the decay amplitude of spin 1 diquarks in the same way as one writes the well established decay amplitude of vector mesons.

The diquark's decay is obtained as in a normal hadronic decay and the hadronic part of the matrix element is given by

$$<0|A_\mu^+|D^1(cd)> = f^{(1)}_{D(cd)} \; M^{(1)}_{D(cd)} \; \varepsilon_\mu \qquad (5)$$

where A_μ^+ is the axial-vector current, $f^{(1)}_{D(cd)}$ is the decay constant of the axial-vector (cd) diquark of mass $M^{(1)}_{D(cd)}$ and ε_μ

is the polarization vector. The (cd) diquark amplitude has then the same form as the amplitude for the decay $\rho^+ \to \ell^+ + \bar{\nu}_\ell$ i.e,

$$\Gamma^{WE}(D(cd)) = \frac{G^2}{8\pi} \left[f^{(1)}_{D(cd)}\right]^2 \left[M^{(1)}_{D(cd)}\right]^3 . \qquad (6)$$

We now make the further assumption of an equiprobability for the diquark to be either of type (cd) or (cu). Since only the spin 1 contribution is retained, we take $P_{D(cd)} = 1/2$ in eq. (4). Inserting eq. (6) into the W-exchange amplitude for the Λ_c^+ decay, eq. (4), we get, to leading order

$$\Gamma^{WE}(\Lambda_c^+) = \frac{1}{2} \, c_-^2 \, \frac{G^2}{8\pi} \left[f^{(1)}_{D(cd)}\right]^2 \left[M^{(1)}_{D(cd)}\right]^3 \cos^2\theta_C \qquad (7)$$

The above result is reminiscent of the non-relativistic approximation of ref. 4 (see also ref. 13).

In (7) we take $M^{(1)}_{D(cd)} \simeq 1910$ MeV as estimated in ref. 2 and $f^{(1)}_{D(cd)} \simeq 181$ MeV as calculated in ref. 6. Furthermore, we take $\cos\theta_C \simeq 0.97$. Thus we find, for the W-exchange contribution to the Λ_c^+ decay width, the result

$$\Gamma^{WE}(\Lambda_c^+) \simeq 3.87 \;\; 10^{12} \; \sec^{-1} \qquad (8)$$

We now have to correct the above result to take the contribution of W-radiation into account. To avoid effects connected with the quark masses in this part of the amplitude, we use the approach of ref. 4, that is, we use the experimental result on the D^+ lifetime which, as already mentioned, is dominated by W-radiation. We write

$$\Gamma^{tot}(\Lambda_c^+) = \Gamma^{WE}(\Lambda_c^+) + \Gamma^{WR}(\Lambda_c^+) \simeq \Gamma^{WE}(\Lambda_c^+) + \Gamma(D^+) \qquad (9)$$

and the Λ_c^+ lifetime is then given by

$$\tau_{\Lambda_c^+}^{tot} = \tau_{D^+}^{exp} \left[1+\Gamma^{WE}(\Lambda_c^+)\, \tau_{D^+}^{exp}\right]^{-1} \qquad (10)$$

For $\tau_{D^+}^{exp}$ we use the world average[7]

$$\tau_{D^+}^{exp} = 8.2^{+1.1}_{-0.9} \cdot 10^{-13} \text{ sec} \qquad (11)$$

obtained as the weighted average[7] of the various measurements ranging between 4 to 12 10^{-13} sec. Eq. (11) combined with eq. (10) gives

$$\tau_{\Lambda_c^+}^{tot} \simeq 1.97 \cdot 10^{-13} \text{ sec} \qquad (12)$$

as compared with the experimental average[7]

$$\tau_{\Lambda_c^+}^{exp} \simeq 2.2^{+0.7}_{-0.4} \cdot 10^{-13} \text{ sec} \qquad (13)$$

The agreement with our theoretical prediction (12) and the experiment is excellent. Notice also that the whole philosophy of the paper consisting in assuming that, of the two mechanisms, W-exchange is the dominant one, is proven correct. Ignoring W-radiation, from eq. (8) we would in fact have $\tau_{\Lambda_c^+}^{WE} \simeq 2.58\ 10^{-13}$ sec, which proves that, in fact, W-radiation is of the order of 20%.

In a previous paper[11], we have argued that a quantum-mechan ical equilibrium between the two diquark configurations (cd) and (cu) could lead to a mass splitting for the Λ_c^+ thus explaining this experimental finding (see ref. 11 for the literature on the subject). In this paper, we have not entered into the problem of how these two different states could contribute to the properties of Λ_c^+ decay because this would require a much more detailed investigation of how the two contributions of W-exchange and W-radiation affect the various decay channels.

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