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SEARCH FOR DIQUARK SUBSTRUCTURES IN CHARMED BARYON SPECTROSCOPY

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A B S T R A C T

We suggest that the present experimental evidence for two Λ_c^+ mass levels may have a deep physical significance and can be taken as the first hint of (cu) and (cd) diquark substructures within the baryon.

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Diquark structures of constituent quarks were suggested long ago ¹⁾ to be a handy tool for describing baryons. If, in fact, one considers quarks as belonging to the fundamental representation of $SU(3)$ [$SU(4)$ including charm], the diquark would have the content $3 \times 3 = \bar{3} + 6$ where the coupling is attractive in the $\bar{3}$ and repulsive in the 6 representations, respectively. Thus the diquark would "bind" in the $\bar{3}$ where it would have the $SU(3)$ content of an antiquark. In this case a qqq system being of the form Dq (with $D = qq$) and being D analogous to $\bar{q}$, would be somewhat similar to a $\bar{q}q$ system, i.e., to a meson. Thus, baryons could be studied as two-body bound states. In spite of this appealing property of diquarks, the question of whether or not they may indeed be considered as realistic substructures within the baryons is still completely open. The reason, quite obviously, is that diquarks, like quarks, cannot be liberated because of colour. Thus, only indirect evidence of their existence can be looked for. A recent attempt in this direction is related to the possible detection of diquark jets ²⁾. In Ref. 2), this point is considered in detail and the previous literature is referred to.

In this paper, we take a different attitude and we look for effects of diquark substructures in charmed baryon spectroscopy. The details of the calculations will be published elsewhere.

The idea is the following. If diquarks exist as unstable substructures within the baryons, the latter ought to be the result of a dynamical equilibrium occurring between the various competing substructures. In this case, we expect well-known quantum mechanical effects to give rise to a level splitting of the ground state. This effect is presumably difficult to look for in the case of a baryon composed of three light quarks since we feel that in this case one should use a fully relativistic approach ³⁾ which makes it doubtful that one can resort to a potential model description ⁴⁾. Furthermore, in this case one would have three competing substructures to deal with at the same time. By contrast, if one of the constituent quarks is much heavier than the other two, one can describe the physical situation either as resulting from the dynamical equilibrium between two competing substructures, whereby one light quark is "bound" by the field of the diquark composed of the second light quark with the heavy one (ignoring the effect of the "light" diquark bound to the heavy quark) or, alternatively, as the dynamical equilibrium between the two substructures described by the "light" diquark bound to the heavy quark and the average of the two heavy diquarks binding the last light quark. In either case a tunnel effect is expected to occur between these two configurations yielding a splitting of the ground state in two levels. For simplicity, here we shall refer to the first of the two above

mentioned configurations and we shall ignore all quantum number complications. Thus, the natural candidate to look for the previous energy splitting is the (cud) charmed baryon, i.e., the Λ_C^+ .

With all due differences, the mechanism is completely analogous to the one at work in the case of the ammonia molecule where two symmetric configurations of the nitrogen atom (with respect to the plane where the three H atoms lie) are in dynamical equilibrium. Two eigenfunctions of the Hamiltonian encounter here, the symmetric and the antisymmetric one, whose energy splitting is responsible for the oscillations which give rise to the effect known as Maser ⁵⁾.

After having set the stage for the effect we are looking for, it is appropriate to recall that the experimental situation for Λ_C^+ production is indeed rather controversial since two sets of measurements exist, giving 2260 MeV/c² and 2280 MeV/c² as average values for the Λ_C^+ mass. The situation is summarized in Table 1 ^{6),7)}. With all due care and reservation, this can be taken as a hint that the effect we are looking for should give a mass splitting of the ground state of the Λ_C^+ (cud) system of the order of ~20 MeV/c². Such a value is large enough to be experimentally detectable and small enough to make us confident that we can presumably apply a non-relativistic approach.

To see whether our point can be made somewhat more quantitative, we have used a very simple-minded approach with a two-sided harmonic potential

$$V(x) = \frac{1}{2} \mu \omega^2 (|x| - a)^2 \quad (1)$$

which is shown in the Figure (where $V_0 = \frac{1}{2} \mu \omega^2 a^2$). Here the over-all confining well is taken to be quadratic instead of linear or logarithmic as is usually the case ⁸⁾ but this should be quite immaterial for our problem ⁹⁾.

In the following we denote by $E_0 = \frac{1}{2} \hbar \omega$ the unperturbed energy value of the ground level which one would find with a single harmonic potential and with E_1 and E_2 the two resulting energy levels.

Standard treatment of the problem ¹⁰⁾ in the case $V_0 \gg E_0$ gives, for the level splitting

$$V_0 = \frac{1}{2} \mu \omega^2 a^2 \Rightarrow \omega = (2V_0 / \mu a^2)^{1/2} \quad (2)$$

$$\Delta E = 2 \hbar \omega \left(2V_0 / \hbar \omega \pi \right)^{1/2} \exp[-2V_0 / \hbar \omega] \quad (3)$$

We have here the three parameters to adjust, the reduced mass μ

$$\mu = m_q m_D / (m_q + m_D) \quad (4)$$

(where m_q is the mass of the light quark and m_D that of the diquark), the height of the potential V_0 and the size of the hadron $2a$. For a we choose a "reasonable" value $0.4 \lesssim a \lesssim 0.45$ Fermi and we expect μ to be of the order $270 \lesssim \mu \lesssim 320$ MeV/c² if the standard values $m_u \approx m_d \approx 325$ MeV/c² and $m_c \approx 1.5$ GeV/c² are used.

To estimate V_0 [i.e., ΔE , see Eq. (2)] we have proceeded as follows. Given that E_0 is the average value of the two levels E_1 and E_2 , we take, as an additional condition of our problems

$$E_0 = \frac{1}{2} \hbar \omega \approx 2260 \text{ MeV} + \Delta E / 2. \quad (5)$$

It turns out that this condition restricts the possible values of V_0 in the range $12000 \lesssim V_0 \lesssim 16000$ MeV in order that Eq. (3) admits solutions.

The result of the calculation for various values of the different parameters with the constraint (5) is shown in Table 2. Typically the range of values of E is of the order $10 \lesssim E \lesssim 30$ MeV which is just the right order of magnitude one expects to comply with the experimental discrepancy exhibited in Table 1.

Aside from the fact that the data are presently much too scant as to allow for any definite conclusion, the point is that the mechanism proposed offers an extremely suggestive explanation of the experimental finding of two levels of Λ_c^+ as being due to the two dominant diquark substructures which are in dynamical equilibrium. Many comments are in order. First of all experimental confirmation that both levels $\Lambda_c^+(2260)$ and $\Lambda_c^+(2280)$ exist and that the present experimental finding is not a fluctuation due to experimental resolution is badly needed. Secondly, the same effect should be present in Σ_c where, according to our approach, one should again find two energy levels with a splitting of the same order of magnitude $\Delta E \approx 15 \pm 10$ MeV. The third point is that the analogous splitting that one

should find in bottom spectroscopy is totally insignificant [with the present parameters but much larger V_0 , one finds, at the very best, $\Delta E \approx 0(10^{-4} \text{ MeV})$]. The last point is that the present approach could perhaps be stretched to apply to masses as low as that of the strange quark to discuss the spectroscopy of sud , suu , sdd particles, i.e., of the usual strange hyperons. It is interesting in this context to notice that the hyperfine baryon spectroscopy of Isgur and Karl ¹¹⁾ is at its worst in the sector of the strange baryons. Should one apply the present considerations to the $\text{sq}\bar{q}$ system taking into account only the $(\text{sq}_1)\bar{q}_2$ and $(\text{sq}_2)\bar{q}_1$ substructures and not the third possibly competing one $\text{s}(\bar{q}_1\bar{q}_2)$, one would find an energy splitting which can easily be of the order of 100-200 MeV.

Two problems are, however, present here : i) is it reasonable to apply the present considerations based on a potential approach to relatively light quarks ? and ii) if it is reasonable, one should find a simple enough prescription to take into account simultaneously the three competing substructures.

Finally, we would like to point out that we are well aware that a "realistic" spectroscopy of baryons should take into account many more complications (spin forces, three-dimensional interactions, different quantum numbers for the various levels, etc.) than we have considered here. Our point of view, however, is that such extra complications would have clouded the simple physical picture discussed here as our principal aim was to point out the possibility that we may be witnessing, in the two experimental levels of Λ_c^+ , the first indirect evidence of diquark substructures within the hadrons.

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Mass (GeV)	Reaction	Decay modes	Ref.
Experiments associated to $m_{\Lambda_C^+} \approx 2.26$ (GeV)	2.26 $\nu p \rightarrow \mu^- \Lambda_C^+ \pi^+ \pi^+ \pi^-$	$\Sigma_C^{++} \rightarrow \Lambda_C^+ \pi^+$ $\downarrow$ $\Lambda \pi^+ \pi^+ \pi^-$	6a)
	2.260±0.010 γ induced	$\bar{\Lambda}_C^+ \rightarrow \bar{\Lambda} \pi^- \pi^- \pi^+$	6b)
	2.254±0.012 $\nu n \rightarrow \mu^- \Lambda_C^+$	$\Lambda_C^+ \rightarrow K^{*-} p \pi^+$	6c)
	2.26 $pp \rightarrow p K^- \pi^+ X$	$\Lambda_C^+ \rightarrow p K^- \pi^+$	6d)
	2.255±0.002 $pp \rightarrow p X$	$X \rightarrow \Lambda_C^+ + D + n\pi$ $\downarrow$ $\{ K^- p \pi^+ \}$ $\Lambda \pi^+ \pi^+ \pi^-$	6e)
	2.257±0.010 $\nu p \rightarrow \mu^- \Lambda_C^+$	$\Lambda_C^+ \rightarrow Y^{*+} \pi^+ \pi^- \rightarrow \Lambda \pi^+ \pi^+ \pi^-$ $\Lambda_C^+ \rightarrow \{ \Lambda \pi^+ \}$ $\bar{K}^0 p$	6f)
	2.262±0.010 $pp \rightarrow X + \bar{C}_1 + C_2$ 2.245±0.010 $pp \rightarrow X + C_1 + \bar{C}_2$	$C_2 \rightarrow \Lambda_C^+ \rightarrow K^- p \pi^+$ $\bar{C}_2 \rightarrow \bar{\Lambda}_C^+ \rightarrow K^+ \bar{p} \pi^-$	6g)
Experiments associated to $m_{\Lambda_C^+} \approx 2.28$ (GeV)	2.280 2.290 $pp \rightarrow \Lambda \pi^+ \pi^+ \pi^- + X$ $pp \rightarrow K^- \pi^+ p + X$	$\Lambda_C^+ \rightarrow \Lambda \pi^+ \pi^+ \pi^-$ $\Lambda_C^+ \rightarrow K^- \pi^+ p$	7a)
	2.295±0.015 ν induced	$\Lambda_C^+ \rightarrow p \pi^+ K^-$	7b)
	2.285±0.006 $e^+ e^- \rightarrow \Lambda_C^+ \bar{\Lambda}_C^+$	$\Lambda_C^+ \rightarrow p K^- \pi^+$ $\bar{\Lambda}_C^+ \rightarrow \bar{p} K^+ \pi^-$	7c)
	2.290±0.003 ν induced	$\Sigma_C^+ \rightarrow \Lambda_C^+ \pi^0$ $\downarrow$ $K^- p \pi^+$	7d)
	2.285±0.005 2.280±0.003 $\nu p \rightarrow \mu^- p K^- \pi^+ \pi^+$	$\Lambda_C^+ \rightarrow p K^- \pi^+$	7e)
	2.284±0.005 γ induced	$\Lambda_C^+ \rightarrow p K_S^0$ $\bar{\Lambda}_C^+ \rightarrow \bar{p} \bar{K}_S^0$	7f)

Table 1 - Various experiments for Λ_C^+ production classified according to the two values encountered for the mass.

a (Fermi)	μ (MeV)	V_o (MeV) $\times 10^3$	ΔE (MeV)	$E_2 = E_1 + \Delta E =$ 2260 + ΔE (MeV)
0.42	295	13.8	29.11	2289.11
0.42	300	14.0	26.64	2286.64
0.43	290	14.2	24.65	2284.65
0.43	300	14.7	20.17	2280.17
0.44	295	15.1	17.00	2277.00
0.44	305	15.6	13.82	2273.82
0.45	290	15.5	14.35	2274.35
0.45	300	16.0	11.60	2271.60

Table 2 - Range of values of the parameters used and of the corresponding splitting (the lower level has been fixed at $E_1 = 2260$ MeV).

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FIGURE CAPTION

The potential $V(x)$ as a double coupled harmonic oscillator.

FIG. 1