Λ_s(1405) and Negative Parity Baryon States

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Abstract

After a brief historical background on the Λ_s(1405), we revisit the 25 year old controversy on whether Λ_s(1405) is a qqq (L=1) three quark state or a \( \bar{K}N \) quasi virtual bound state. This work is stimulated by the recent suggestion of Isgur that s be treated as a heavy quark in heavy quark effective theory HQET. We re-examine the empirical evidence for minimal mixing amongst singlets and octets in negative parity baryon states, with a possible dynamical origin in the opening of inelastic threshold channels. Finally, we suggest that Λ_s(1405) belongs to a class of hadrons which are described simultaneously as qqq or \( q\bar{q} \) states and as hadronic bound states.

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The Λ_s(1405) (=uds, similarly for Λ_c=udc, Λ_b=udb) state with \( I = 0, J^P = 1/2^- \) was predicted in 1959 [1] by extrapolating into the unphysical region below \( K^-p \) threshold for \( K^-p \rightarrow \pi + \Sigma \) reaction amplitude, using zero effective range S-wave scattering lengths obtained from \( \bar{K}N \) data above threshold. It was discovered experimentally some two years later by the LBL Bubble Chamber Group [2]. As attested by the compilation in for instance the latest Particle Data Group book [2], refined effective range analysis with accumulated \( \bar{K}N \) data have always been able to reproduce width and mass parameters of Λ_s rather well. Furthermore there is the telltale signal of association with the \( \bar{K}N \) threshold in that the Λ_s(1405) resonant shape cut-off sharply at this threshold. The question of whether Λ_s(1405) is described correctly as a \( \bar{K}N \) bound state or a three quark state has been discussed extensively with no definite conclusion [3]. There is the suggestion from the chiral cloudy bag model [1] that the \( \bar{K}N \) configuration dominates at the 90\% level over the three quark configuration, and is supported by more recent work [3]. Hence it was never seriously doubted that \( \bar{K}N \) closed channel was significant in the formation of Λ_s(1405), and in fact it was a shock to have to think of this state in another way as discussed below.

Nevertheless it has been recognized that quark model classification is fundamental for all hadronic matter, hence Λ_s(1405) must have assignment in the quark model [3]. The standard \((qqq, L = 1^-)\) SU(6) 70 representation of the quark model accommodates Λ_s(1405) and a companion Λ_s(1520) in \( J^P = 3/2^- \) as the (1,2) and (1,4) (SU(3), 2J+1) members of

\[
(70, L = 1^-) = (8, 6)^- + (10 + 8 + 8 + 1, 4)^- + (10, 2)^- + (8 + 8 + 1, 2)^-.
\]

There has however been a number of problems for this uds classification of Λ_s states, which can be stated as follows:-

(i) The L.S Puzzle. All states which have been assigned to multiplets in (1) have very small spin-orbit L.S contributions [3,4,10] except for the large Λ_s(1520) - Λ_s(1405) splitting of 115 MeV. Indeed a relativized quark model proposed by Capstick and Isgur [10] naturally “explains” the smallness of spin-orbit interaction thus exacerbating the Λ_s(1520)/Λ_s(1405) non degeneracy anomaly. However, the same authors [10] concede
that $\Lambda_s(1405)$ has unusually large couplings to $\bar{K}N$ channel, with respect to which it is an S-wave resonance. Coupling would naturally shift predicted uds state towards or even below $\bar{K}N$ threshold, which is where it is found. As argued by Capstick [11], whenever a quark state is close to a threshold $[\bar{K}N]$ like $\Lambda_s(1405)$, it is inconceivable that the narrow resonance approximation [9,10] used in the calculation of masses will give correct answers - unless by chance!

(ii) At its observed mass the $\Lambda_s(1405)$ can decay only into $\Sigma\pi, \Lambda\gamma$, and $\Sigma\gamma$; one way to test whether it can be interpreted as a mass-shifted version of the uds quark state is to check, in addition to the known $\Sigma\pi$ amplitude, the two radiative decay amplitudes against those expected for the quark state interpretation. Unfortunately the earlier evidence here for the quark interpretation [12] has been vitiated somewhat by the 1991 Burkhardt isobar fit [13] which reported solutions for the branching ratios of $\Lambda_s(1405) \to \Lambda\gamma, \Sigma\gamma$ about an order of magnitude smaller than those arrived at in [12]. There has been some recent work [14] in this area, but no definite conclusions were reached on this issue.

(iii) To underline the gravity of the $\Lambda_s(1405)$ problem, Jaffe [15] has made the drastic suggestion that the large splitting with $\Lambda_s(1520)$ could be better understood by re-assigning $\Lambda_s(1405)$ to be a hybrid baryon $(uds)g$ where $uds$ is in $1/2^+$ and $g$ is the gluon. It seems to us, however [11] that a shift of less than 300 MeV for a hybrid excitation [the $(uds) 1/2^+ \Lambda_s$ is at 1116 MeV] is too small, and it is only the bag model’s treatment of ‘constituent gluons’ which yields these low energies. None of the other low-lying hybrid states predicted by the bag model have as yet surfaced in nature. If it costs only 300 MeV to excite the glue, we would have seen several hybrids in the non-strange spectrum, which is much better known. Although it has been speculated that the Roper resonance $N(1440)$ with $J^P = 1/2^+$ is a nonstrange hybrid baryon, one needs then to ask where is the even lower mass $qqq$ state with those same quantum numbers? In the quark model [10] this $qqq$ state with $I = 1/2$
and $J^P = 1/2^+$ is predicted at about 1550 MeV. Here again the mass prediction for this 3q state resorted to the use of the narrow resonance approximation where in actuality we know that $N(1440)$ has a large width to $N\pi$ [60-70% of a total width $\sim 350$ MeV]. Decay channel couplings probably shifted the quark model prediction at 1550 MeV down to the Roper mass of 1440 MeV, a shift compatible with the $115$ MeV shift downward of the $\Lambda_s(1405)$ from its quark model predicted value of 1520 MeV. Jaffe [15] has recently suggested that the low mass $(uds)g$ applies only to unitary singlets where color magnetism is important. However, the need for a $J^P = 1/2^-$ uds state near $\Lambda_s(1520)$ remains to handle the $L.S$ puzzle.

In a very stimulating recent contribution Isgur [16] argues that recent data from the $\Lambda_c$ system now strongly indicates that the $\Lambda_s(1405)$ is in fact a uds system, thus giving a new twist to the 25 year old $qqq(L = 1)$ vs. $\bar{K}N$ controversy.

In brief, his argument runs as follows:

1) A recent CLEO result [17] gives

$$\frac{\Lambda_s(1520) - \Lambda_s(1405)}{\Lambda_c(2625) - \Lambda_c(2593)} = 3.45 \pm 0.17.$$  \hspace{1cm} (2)

This is to be compared with the HQET prediction of $m_c/m_s$. The agreement can be considered to be reasonable when constituent masses are used.

2) He then argues as follows:-

a) He inverts the argument to say that because (2) is true, ipso facto it is “proof” that s-quark must be heavy in the HQET sense.

b) In HQET, spin structure of $\Lambda_s(1405)$ is fully determined.

c) Therefore $\Lambda_s(1405)$ is a 3q (uds) state and not a $\bar{K}N$ quasi bound state.

However the agreement in Eq. (2) is not quite as good as the other hyperfine splittings [18] e.g.
\[
\frac{K^*(892) - K}{D^*(2010) - D} = 2.830 \pm 0.015 \quad (3a)
\]
\[
\frac{\Sigma^*(1385) - \Sigma}{\Sigma^*_c(2520) - \Sigma_c(2455)} = 2.92 \pm 0.07. \quad (3b)
\]

The agreement in Eq. (2) is noticeably poorer than in Eq. (3) leading us to conclude that the \( \Lambda_s(1520) - \Lambda_s(1405) \) sector remains qualitatively different and that our understanding of this system is still incomplete. The errors in (2) and (3) are experimental where we have used the PDG values.

The \( \Lambda_s(1405) \) as a difficult classification case for the \([70, 1^-]\) quark baryon spectrum, has been an important stimulus in search for other deviations from the standard quark model prediction \([7,10]\). It has been found that there is increasing empirical support for an \((8,2)\) \( \eta \) octet of \(1/2^-\) states \([19,20]\) associated with \( \eta + N[N(1535)], \eta + \Lambda[\Lambda(1670)], \eta + \Sigma[\Sigma(1750)] \) S-wave threshold interaction. Although the \( \eta + \Xi \) member has yet to be identified, such states within say 50 MeV of the appropriate thresholds could satisfy an \textbf{unmixed} Gell-Mann-Okubo octet mass formula to high accuracy. The experimentally known members of the \( \eta \)-baryon octet all have significant coupling to the appropriate \( \eta \)-baryon channel, in the range 15 to 55% in decay partial width. As in the case of \( \Lambda_s(1405) \leftrightarrow \bar{K}N \) \([11]\) these states are close to the \( \eta \) baryon thresholds and have significant couplings to the appropriate \( \eta \)-baryon channels, and there could be sizeable mass shifts from the predictions of the \([70, 1^-] \) \( qqq \) model \([4,10]\). Indeed the S-wave \( 1/2^- \) \( \eta \) octet violates a rule suggested by Feynman \([7]\) for (mass)\(^2\) to wit:-

\[
\text{Sign}[\Sigma^2 - \Lambda^2] = \text{Parity of the state.} \quad (4)
\]

whereas the Isgur-Karl model \([4]\) largely satisfies this rule. (Established \( J^P = 3/2^-, 5/2^- \) octets \([3,20]\) also appear to satisfy this rule.) It is now worthwhile to re-examine the classification of negative parity baryon states of the standard quark model \([10]\) in the light that nature has provided us with unmixed (in the octet mass formula sense) \( \eta \) octet of \( J^P = 1/2^- \) states as well as the earlier \( J^P = 3/2^- \gamma \) octet \([21]\) which has now received impressive experimental support \([20]\). The methods used \([4,12]\) to determine the composition of \( \Lambda_s(1405) \) as a
superposition of three-quark and $K N$ configurations should now be applied to the $\eta$-baryon $1/2^-$ octet to determine their compositions as superpositions of three-quark and $\eta$-baryon S-wave “molecular” configurations. Bugg [22] has stressed that in connection with the $K \bar{K}$ and $\eta \eta$ thresholds in the $0^+$ sector inelastic thresholds can influence both the shape of a resonance and move its mass around by a substantial amount. We suggest that the same is true in the baryon sector not only for $\Lambda_s(1405)$, but also for the $\eta$-baryon octet and indeed the $\gamma$ octet where the $J^P = 3/2^-$ member $N(1512)$ could have a dynamical origin due to the opening of the inelastic $\rho$-N S-wave threshold as proposed many years ago by Ball and Frazer [23]. It has been suggested that the mechanism for $\Lambda_s(1405) - \Lambda_s(1520)$ mass difference is driven largely by $N-\Delta$ and $K-K^*$ mass differences through mixing with nearby threshold. This is an interesting idea, but beyond the scope of our Letter here.

To summarize, we see that there is some evidence that treating the $s$-quark as heavy in HQET [16], together with the corroborative evidence in the meson spectra [24], points towards the interpretation that $\Lambda_s(1405)$ is 3q (uds) in nature. [Although the reason why it is permitted to treat $s$-quark as heavy, when $m_s$ is not large compared to either $\Lambda_{QCD}$ or $m_u, m_d$ (in the constituent basis), remains mysterious.] On the other hand, perhaps even stronger evidence [2,4,5] exists that it is a $\bar{K}N$ quasi virtual bound state in the molecular sense. Hence it seems extremely unlikely that either picture can be “wrong”.

It seems to us that whereas the description in terms of 3 quarks is clear cut for many baryons; at the other extreme there are baryonic states which are quite clearly not well described as quark states [25]. For example, the deuteron is a clear example of a bound state of neutron and proton as demonstrated by powerful arguments given by Weinberg [26]. Furthermore, there is no evidence for other members of the six-quark multiplet. We submit that a state such as $\Lambda_s(1405)$ lies somewhere in the middle. Namely, whereas it is a three quark state and is classified as such; many of its properties, such as production (and formation), mass shift, coupling to various channels are heavily influenced by the proximity of the nearby $\bar{K}N$ threshold and the S-wave nature of the coupling.

A number of other hadronic states have similar behaviour and are influenced strongly by
nearby thresholds. These are:

(I) As already mentioned, the formation of the \( \eta \) and \( \gamma \) octets, is also strongly influenced by nearby inelastic S-wave channels. They are furthermore characterized by mixing purity as a distinguishing feature.

(II) The axial-vector kaons seem to be mixed in ways which favor specific decays, e.g. \( K_1(1270) \to K\rho \) or \( K_1(1400) \to K^*\pi \) in S-waves as noted long ago \[27\]. Similar mixing was also found in \( D^{**} \) states as noticed by de Rújula et al. \[28\]; and a similar tendency in baryons was observed in the Isgur-Karl paper \[9\].

(III) The \( a_0(980) \) and \( f_0(980) \) appear to be prominent effects on the \( I=1 \) and \( I=0 \) \( K\bar{K} \) systems near threshold. Their assignment as \( q\bar{q} \) states is somewhat problematic because of their low \( \gamma\gamma \) widths \[29\]. There are recent proposals for a scalar nonet for both \( q\bar{q} \) \[30\] as well as non-molecular \( qq\bar{q}\bar{q} \) \[31\]; but the \( K\bar{K} \) seems to be the dominant component \[32\].

(IV) The \( E/\iota(1420) \) (an \( I=0 \) \( K\bar{K}\pi \) resonance) has a mass such that \( a_0(980) \) and the two \( K^*(890) \) bands in the Dalitz plot all cross at the same point. Perhaps it is a “molecule” of its three final-state particles, in which each pair resonates simultaneously.

(V) There is also the \( \xi(2220) \) \[33\] which may be an example of a state with simultaneous presence of \( gg, q\bar{q}, qq\bar{q}\bar{q}, \) and \( q\bar{q}g \) components. Given its proximity to the \( \Lambda\bar{\Lambda} \) threshold, this could be the key channel.

Recently, Isgur \[34\] has developed a formalism on the impact of thresholds on the hadronic spectrum beyond the adiabatic approximation. We feel that this formalism could and should be applied to a number of phenomenological issues raised here. In particular the threshold shift for \( \Lambda_s(1520) - \Lambda_s(1405) \) problem discussed by us qualitatively, can now be given a quantitative basis. Hence this formalism has a number of other potential applications, as listed above under (I) to (V), where it makes sense to view hadronic
states simultaneously as states containing the lowest number of quarks (e.g. $q\bar{q}$ or $qqq$) and as bound states or resonances involving specific channels (and hence involve additional $q\bar{q}$ pairs).

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