

# The End of the Constituent Quark Model?

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**Abstract.** In this conference summary talk at Hadron03, questions and challenges for Hadron physics of light flavours are outlined. Precision data and recent discoveries are at last exposing the limitations of the naive constituent quark model and also giving hints as to its extension into a more mature description of hadrons. These notes also pay special attention to the positive strangeness baryon  $\Theta^+(1540)$  and include a pedagogic discussion of wavefunctions in the pentaquark picture, their relation with the Skyrme model and related issues of phenomenology.

## Introduction

My brief was to concentrate on light hadrons; but where do heavy hadrons end and light begin? I shall focus on what heavy flavours can teach us about light, and vice versa. The possible discovery of an exotic and metastable baryon with positive strangeness, the  $\Theta^+(1540)$ , has led to an explosion of interest in recent months and throughout this conference. There was a dedicated discussion session about it, which highlighted much confusion. In the hope of clarifying some of the issues, I have decided to devote a considerable part of this summary to a pedagogic description of wavefunctions and a review of some of the emerging literature that drew comment at the conference.

## Light Hadron Spectroscopy and Dynamics: Present and Future

As regards the future of light hadrons experimentally: we have heard of several examples of innovative methods involving high energy machines. In particular, we have electron positron machines designed as B-factories, which turn out to access lower energies as a result of the initial state radiation[1]. They also provide copious data on  $\gamma\gamma \rightarrow$  light hadrons. At HERA we have vector mesons produced diffractively but also now charge conjugation positive states produced apparently in the rapidity gap between the photon and the target proton[2]. Then there is the new opportunity for central production in proton-proton collisions at STAR and the proposal for this at HERA-g [3]. Exploiting the  $dk_T$  filter and  $\phi$  dependences may separate  $q\bar{q}$  states from those with gluonic admixtures or S-wave substructure (see later)[4].

Then we have heard about B and D decays into light hadrons from BaBar, BELLE and FOCUS and novel ideas from Ochs about  $B \rightarrow K^* + 0^{++}$  as an entree into the light scalars[5]. There is also  $D_s \rightarrow \pi(s\bar{s})_{0^{++}}$  which gives an entree to the scalar  $s\bar{s}$  sector. The decays  $\psi \rightarrow \gamma\gamma V$ , where  $V \equiv \rho, \phi$  have been reported from BES[6] and will be

pursued by CLEO-c [7]. So far these data have been applied to the  $\iota(1440)$ [6] region but eventually promise to provide information on the flavour content of any  $C = +$  mesons, through  $\psi \rightarrow \gamma R(C = +) \rightarrow \gamma \gamma V$ . In particular for  $R \equiv 0^{++}$  this can give essential information on the flavour contents, and hence mixings with the glueball of lattice QCD, of the various scalar mesons[8].

When high statistics data are available at CLEO-c and BES-III we can study  $\chi \rightarrow \pi + R$  where  $R \equiv$  light hadrons and complement the old  $p\bar{p}$  data from LEAR. The bonus will be that  $\sqrt{s} \sim 3.5\text{GeV}$  and that the overall  $J^{PC}$  is known in the subsequent partial wave analyses. Of particular interest here could be  $\chi \equiv 1^{++}$  where in S-wave the recoil system  $R \equiv 1^{-+}$ , which is the exotic channel favoured for hybrid mesons. So there are reasons to be optimistic about sorting out light hadron spectroscopy and dynamics and solving whether and how the gluonic degrees of freedom are manifested in the strong QCD regime.

As G.W.Bush and T. Bliar might summarise the search for missing glueballs and hybrids: we know they exist; they are hidden but we will find them; give us time - we have only been searching for 20 years.

We have also heard[6] how  $\psi$  decays can give novel insights into baryon resonances in the timelike region through  $\psi \rightarrow \bar{N}N^*$  or  $\Delta\Delta^*$ . This selects isospin states apart from a background due to the intermediate  $\psi \rightarrow \gamma^*$  channel, and gives complementary information to that from the maturing data from Jefferson Laboratory[9]. Finally we have the degeneracy of the hybrid candidate  $\pi(1800)$  and  $D(1865)$ . The Cabibbo suppressed decays of the latter[10] share common channels with the strong decays of the former. Disentangling this is a significant overlap between heavy and light flavours of a pragmatic nature let alone the interesting potential implications for novel physics.

A problem in light hadron dynamics is that not all of the data can be correct. Swanson[11] has shown a nice figure listing all of the mesons as a function of  $J^{PC}$  from the PDG which is clearly overpopulated. This leads me to two requests: one to theorists and one to experimentalists.

Theorists: beware of taking your favourite random model; finding the  $J^{PC}$  states that agree with it and then ignoring, excusing or tweaking the model to apologise for those that do not. It is important to keep the big picture in mind if we are to progress. Focus on the wood not the trees. There is information on more than spectroscopy. We have decays and also production dynamics that can provide essential constraints on models and interpretation.

Experimentalists: what am I supposed to regard as "official" data? Is a conference presentation, which does not get refereed for a peer reviewed journal "official"? At this Hadron series over the years we have seen reports of measurements on say phenomenon H1. Nothing is seen in a peer reviewed journal. Two years later the same group might report the phenomenon as H2; or they might say nothing and only when questioned by those in the know reveal that they no longer see any signal. However, this is not reported as an "official" withdrawal. It is hard enough trying to interpret the data without the added pollution of work in process. In particular, it is extremely important that states which are claimed, and then go away, be reported as withdrawn.

I would not want to stifle the presentation of preliminary data, as such creates discussion that can be mutually informative. However, when it is written up for the proceedings I would urge that a clear statement be made up front as to the status of the report: e.g.

on what timescale will a version be prepared for “official” publication? If the data are even more preliminary, I would suggest that no written summary be produced for the proceedings; or that a clear disclaimer be made that this is a report on an individual’s analysis. I would hope that any such presentation has received the endorsement of the group, but suspect that this is not always the case, since at this conference I have heard at least one parallel session where group members appeared to be hearing of some analysis for the first time. This is fine for enabling the “critical filtering” that produces the best analyses, but dangerous nonetheless if associated “health warnings” are not prominent.

As regards the (scalar) glueball and hybrid states it is time to move on from simple ideas that such states exist in some pure sense. We have heard many times here statements on the line of “The  $f_0(xxxx)$  is the scalar glueball”, where you are invited to insert your number of choice out of 970,1300,1500 or 1700. And for the hybrid: “The  $\pi_1(yyyy)$  is exotic, ergo it is hybrid” (where yyyy is 1400, 1600 or 1800). The only pattern seems to be that the former set involve odd and the latter even numbers in their first two places.

What I offer here is not a solution, but needs to be taken into account when seeking the solution. The real world contains thresholds for hadronic channels with the same  $J^{PC}$  as these objects and will involve mixings with those as well as between the primitive glueball and  $q\bar{q}$  flavoured states. So the scalar mesons with  $I=0$  in the PDG will be mixtures of glueball and flavoured  $q\bar{q}$  at least. (Hence the interest in  $\psi \rightarrow \gamma\gamma V$  alluded to earlier to help disentangle this mixing). Likewise with the  $\pi_1$  states. The non-relativistic quark model was built, in part, on the absence of such exotic  $J^{PC}$  combinations. Now we have three being claimed. This is too much of a good thing and the presence of S-wave thresholds such as  $\pi b_1$  and  $\pi f_1$  around 1400MeV surely plays some essential role. Another school of thought has been presented here: could some of the  $\pi_1$  states be evidence for  $qq\bar{q}\bar{q}$  in  $10\pm\mathbf{10}$  configurations[12]? Possibly, but beware the dog that didn’t bark in the night: invoking multi-quarks to accommodate one or two awkward states also implies the existence of whole multiplets of associated states. The failure to see them also needs to be explained in such models.

There is rather general agreement now that qualitatively the scalar mesons sector contains a scalar glueball degree of freedom[13] in the data, the question now is to quantify it. In this regard there seem to be two broad schools[14, 15] and data need to be able to distinguish between these as a minimum before we can claim the glueball as proven. First their common features: there is a scalar glueball present in the mass region up to around 1700MeV, which mixes with and disturbs the “simple” isoscalar  $q\bar{q}$  sector. Now for their details. One[14] is that the mesons above 1GeV,  $f_0(1700; 1500; 1370)$  are the  $I=0$  states of  $q\bar{q}$  mixed with the  $G$ , and that  $K(1430)$  and  $a_0(1450)$  are the other members of the extended nonet; in this scenario the mesons below 1GeV, in particular the  $f_0(980)$  and  $a_0(980)$  have a  $qq\bar{q}\bar{q}$  or dimeson dynamical structure[16, 17]. The other[15] is that the  $f_0(980)$  and  $a_0(980)$  are in the nonet with the  $f_0(1500)$  and  $K(1430)$  (the  $f_0(980)$  and  $f_0(1500)$  having an interesting “inversion” of properties in  $SU(3)$  flavour to the pseudoscalar  $\eta$  and  $\eta'$ ); the  $f_0(1370)$  is not recognised as a real resonance state, the  $a_0(1450)$  if it exists is in some other nonet (perhaps with the  $f_0(1700)$ ); the  $\kappa$  is not resonant and the  $\sigma(600)$  is part of a very broad scalar glueball whose effects are felt throughout an extended energy range.

As I have shares in one of the above pictures, the following observations on the novel meson states reported at this conference might be distorted by my prejudices, but with

that caveat in mind I offer them for consideration nonetheless.

## When does the quark model work?

There is general agreement that the NRQM is a good phenomenology for  $b\bar{b}$  and  $c\bar{c}$  states below their respective flavour thresholds. Taking  $c\bar{c}$  as example we have S states ( $\eta_c, \psi, \psi(2S)$ ), P-states ( $\chi_{0,1,2}$ ) and a D-state ( $\psi(3772)$ ), the latter just above the  $D\bar{D}$  threshold. Their masses and the strengths of the E1 radiative transitions between  $\psi(2S)$  and  $\chi_J$  are in reasonable accord with their potential model status. In particular there is nothing untoward about the scalar states.

Do the same for the light flavours and one finds clear multiplets for the  $2^{++}$  and  $1^{++}$  states (though the  $a_1$  is rather messy); it is when one comes to the scalars that suddenly there is an excess of states. An optimist might suggest that this is the first evidence that there is an extra degree of (gluonic) freedom at work in the light scalar sector. But there is more: there is a clear evidence of states that match onto either  $qq\bar{q}\bar{q}$  or correspondingly meson-meson in S-wave.

Such a situation is predicted by the attractive colour-flavour correlations in QCD[16, 17]. Establishing this has interest in its own right but it is also necessary to ensure that one can classify the scalar states and then identify the role of any glueball by any residual distortion in the spectrum. It is in this context that discoveries this year of narrow states in the heavy flavour sector provide tantalising hints of this underlying dynamics elsewhere in spectroscopy. If this is established it could lead to a more unified and mature picture of hadron spectroscopy.

The sharpest discoveries this year have involved narrow resonances:  $c\bar{s}$  states, probably  $0^+, 1^+$ , lying just below  $DK, D^*K$  thresholds; and  $c\bar{c}$  degenerate with the  $D^o D^{*o}$  threshold. These are superficially heavy flavour states and out of my remit, but their attraction to these thresholds involves light quarks and links to a more general theme which I shall develop below.

First note how we have been reminded here by Barnes[18] that the  $c\bar{c}$  potential picture gets significant distortions from the  $DD$  threshold region, such that even the  $c\bar{c}$   $\chi$  states can have 10% or more admixtures of meson pairs, or four quark states, in their wavefunctions. Also Cahn[19] reminded us that the simple potential models of the  $D_s$  states are inadequate to explain the 2.32GeV and 2.46GeV masses of these novel states as simply  $c\bar{s}$  in some potential. Furthermore, Davies[20] showed that the lattice seems to prefer the masses to be higher than actually observed, though the errors here are still large. In summary there is an emerging picture that these data on the  $D_s$  sector (potentially  $0^+$  and  $1^+$  and the S-wave  $DK$  and  $D^*K$  thresholds) and the  $c\bar{c}$  sector (with the S-wave  $D^o D^{*o}$  thresholds) confirm the suspicion that the simple potential models fail in the presence of S-wave continuum threshold(s).

Now let's examine this in the light flavoured sector. The multiplets where the quark model works best are those where the partial wave of the  $q\bar{q}$  or  $qqq$  is lower than that of the hadronic channels into which they can decay. For example, the  $\rho$  is S-wave  $q\bar{q}$  but P-wave in  $\pi\pi$ ; as S-wave is lower than P-wave, the quark model wins; by contrast the  $\sigma$  is P-wave in  $q\bar{q}$  but S-wave in  $\pi\pi$  and in this case it is the meson sector that wins and

the quark model is obscured.

A similar message comes from the baryons. The quark model does well for the  $\Delta$  (S-wave in  $qqq$  but P-wave in  $\pi N$ ); at the P-wave  $qqq$  level it does well for the  $D_{13}$ , which as its name implies is D-wave in hadrons, but poorly for the  $S_{11}$  which is S-wave in  $N\eta$ . The story repeats in the strange sector where the strange baryons with negative parity would be  $qqq$  in P-wave: the  $D_{03}(1520)$  is fine but the  $S_{01}(1405)$  is the one that seems to be contaminated with possible  $KN$  bound state effects.

As an exercise I invite you to check this out. It suggests a novel way of classifying the Fock states of hadrons. Instead of classifying by the number of constituent quarks, list by the partial waves with the lowest partial waves leading. Thus for example

$$0^{++} = |0^-0^-(qq\bar{q}\bar{q})\rangle_S + |q\bar{q}\rangle_P + \dots$$

while

$$1^{--} = |q\bar{q}\rangle_S + |0^-0^-(qq\bar{q}\bar{q})\rangle_P + \dots$$

or

$$\Delta(1230) = |qqq\rangle_S + |\pi N(qqqq\bar{q})\rangle_P + \dots$$

This holds true for

$$2^{++} = |q\bar{q}\rangle_P + |0^-0^-(qq\bar{q}\bar{q})\rangle_D + \dots$$

the relevant S-wave vector-meson pairs being below threshold. For the remaining P-wave  $q\bar{q}$  nonet with  $C=+$  we have a delicate balance

$$1^{++} = |q\bar{q}\rangle_P + |0^-1^-\rangle_S + \dots$$

where the  $\pi\rho$  S-wave distorts the  $q\bar{q}$   $a_1$ , as is well known; the  $f_1(1285)$  is protected because the two body modes are forbidden by G-parity; for the strange mesons the  $K^*\pi$  and  $K\rho$  channels play significant roles in mixing the  $1^{++}$  and  $1^{+-}$  states while the  $s\bar{s}$  state is on the borderline of the  $KK^*$  threshold.

Chiral models which focus on the hadronic color singlet degrees of freedom are thus the leading effect for the  $0^{++}$  sector but subleading for the vectors. An example was presented[21] where the  $N_c$  dependence of the coefficients of the chiral Lagrangian was studied. In the  $N_c \rightarrow \infty$  limit it was found that  $\Gamma(\rho) \rightarrow 0$ , like  $q\bar{q}$  whereas  $\Gamma(\sigma) \rightarrow \infty$ , like a meson S-wave continuum. Thus there appears to be a consistency with the large  $N_c$  limit selecting out the leading S-wave components.

Conversely, the "valence" quark model can give the leading description for the vectors or the  $\Delta$  but there will be corrections that can be exposed by fine detail data. The latter are now becoming available for the baryons from Jefferson Laboratory; the elastic form factors of the proton and neutron show their charge and magnetic distributions to be rather subtle, and the transition to the  $\Delta$  is more than simply the M1 dominance of the quark model. There are E2 and scalar multipole transitions which are absent in the leading  $qqq$  picture. The role of the  $\pi N$  cloud is being exposed; it is the non-leading effect in the above classification scheme. As we shall see later, the  $\Theta^+(1540)$  as a pentaquark inspires novel insights into a potential pentaquark - or  $N\pi$  cloud - component in the  $N$  and  $\Delta$ .

The message is to start with the best approximation - quark model or chiral - as appropriate and then seek corrections.

Bearing these thoughts in mind it highlights the dangers of relying too literally on the quark model as a leading description for high mass states unless they have high  $J^{PC}$  values for which the S-wave hadron channels may be below threshold. It also has implications for identifying hadrons where the gluonic degrees of freedom play an explicit role and cannot simply be subsumed into the collective quasi-particle known as the constituent quark. Such states are known as glueballs and hybrids.

The lightest glueball is predicted to be scalar[13] for which the problems arising from the S-wave thresholds have already been highlighted. At least here, by exploiting the experimental strategies outlined at the start of this talk, we are possibly going to be able to disentangle the complete picture. For the  $2^{++}$  and  $0^{-+}$  glueballs above 2 GeV there are copious S-wave channels open, which will obscure the deeper "parton" structure. Little serious thinking seems to have been done here.

For the exotic hybrid nonet  $1^{-+}$  we have a subtlety. In the flux-tube models abstracted from lattice QCD, the  $q\bar{q}$  are in an effective P-wave[22, 23], which we may describe by  $|q\bar{q}g\rangle_P$ . There is a leading S-wave  $0^{-+}$  meson pair at relatively low energies, such that

$$1^{-+} = |0^{-+}\rangle_S + |q\bar{q}g\rangle_P + \dots$$

The S-wave thresholds for  $\pi b_1$  and  $\pi f_1$  are around 1400MeV, which is significantly below the predicted 1.8GeV for lattice or model hybrids and tantalisingly in line with one of the claimed signals for activity in the  $1^{-+}$  partial wave. All is not lost however; a  $q\bar{q}$  or  $q\bar{q}g$  nonet will have a mass pattern and decay channels into a variety of final states controlled by Clebsch-Gordan coefficients whereas thresholds involve specific meson channels. These can in principle be sorted out, given enough data in a variety of production and decay channels, but it may be hard.

## SKYRMION MEETS THE QUARK

In the above we have discussed where components beyond the leading  $q\bar{q}$  or  $qqq$  may obscure the simple quark model. We now come to a case where the **leading** component involves five constituents. If this discovery is confirmed it will make a sobering reminder that there can be phenomena latent in data that have been overlooked perhaps for decades.

In the textbooks, one of the major planks in establishing the constituent quark model is the absence of baryons with strangeness +1. The announcement of such a particle, and with a narrow width is therefore startling, if confirmed[24]. It is easy to accommodate positive strangeness; you just allow an extra  $q\bar{q}$  to be present, e.g.  $uudd\bar{s}$ . The problem though is that such a state would be expected to fall apart so rapidly that its width would be broad. A narrow width, signaling metastability, therefore implies the existence of some inhibiting factor. Its parity is undetermined and that could itself discriminate among models. The state was predicted in the Skyrme model[26] where it is a member of a  $\mathbf{10}$  with  $J^P = \frac{1}{2}^+$ . This is already an interesting conundrum for a quark model where the naive expectation is that the lightest state of a pentaquark  $uudd\bar{s}$  has all constituents

in a relative S-wave, hence  $J^P = \frac{1}{2}^-$ . However, this is true only when all the quarks are treated symmetrically. There is a considerable literature that recognises that  $ud$  in colour  $\bar{3}$  with net spin 0 feel a strong attraction, which might even cause the S-wave combination to cluster as  $[udu][d\bar{s}]$  which is the S-wave KN system, while the P-wave positive parity exhibits a metastability such as seen for the  $\Theta$ . Two particular ways of realising this are due to Karliner and Lipkin[28] and Jaffe and Wilczek[29], which I will come to shortly.

A challenge for all quark models is the metastability of the state. The historical stability of the strange hadrons was due to their strong decays being forbidden; the first attempt to describe the  $\Theta$  as a pentaquark[30] built on this idea by proposing that  $\Theta$  be an isotensor resonance with states ranging from  $uuuu\bar{s}$  with charge +3 to  $ddd\bar{s}$  with charge -1. This can give a narrow width as there is no simple decay path that preserves isospin. The colour structure of such a pentaquark system is well defined. The I=2 flavour-space is totally symmetric and so is totally antisymmetric in colour-spin. This forces either  $6_c \times (S=0)$  or  $3_c \times (S=1)$ . Only the latter can combine with the  $\bar{s}$  in  $\bar{3}_c$  to make the colour-singlet baryon. This leads to overall  $J^P = \frac{1}{2}^-$  or  $\frac{3}{2}^-$ . The price, or excitement, is that there is a multiplet of states ( $\Theta^{+++} \dots \Theta^-$ ) to be found. This may be already ruled out if the ELSA[24] data are confirmed as they find the  $\Theta^+$  but have no evidence for any partner, and thus suggest it is I=0.

Models with I=0 suggest that it is at the pinnacle of a flavour  $\bar{10}$ , which is where the original Skyrme prediction would place it. Thus there is also the interesting question of whether or under what circumstances there is any correspondence between the Skyrme and quark pictures.

Attempts to describe this as a pentaquark have been criticised in some quarters on the lines that it is meaningless to describe a hadron as made from a fixed number of quarks or antiquarks. Let's first make some obvious pedagogic remarks in order to accommodate some suggestions that I shall make later.

When the proton is viewed at high resolution, as in inelastic electron scattering, its wavefunction is seen to contain configurations where its three "valence" quarks are accompanied by further quarks and antiquarks in its "sea". The three quark configuration is thus merely the simplest required to produce its overall positive charge and zero strangeness. The question thus arises whether there are baryons for which the minimal configuration cannot be satisfied by three quarks.

A baryon with positive amount of strangeness would be an example; the positive strangeness requires an  $\bar{s}$  and  $qqqq$  are required for the net baryon number, making what is known as a "pentaquark" as the minimal "valence" configuration.

Hitherto unambiguous evidence for such states in the data has been lacking; their absence having been explained by the ease with which they would fall apart into a conventional baryon and a meson with widths of many hundreds of MeV. It is perhaps this feature that creates the most tantalising challenge from the perspective of QCD: why does  $\Theta$  have width below 10MeV, perhaps no more than 1MeV[31].

If the data comprising the evidence as presented at this conference are being correctly interpreted, they suggest that the  $\Theta$  is being produced with probability similar to that of the negative strangeness  $\Lambda(1520)$ . This suggests that the  $\Theta$  is produced by the strong interaction between  $KN$ . However, such a strength seems to be at odds with the implied

feeble decay strength implied by a 1MeV width into  $KN$ , unless perhaps  $\Theta$  is produced by the strong decay from some state  $\Theta^*$ , which is produced strongly by  $KN$  and has width of  $\geq O(100)\text{MeV}$ . The other possibility is that the production cross section of  $\Theta$  is  $O(10-100)$  smaller than that of  $\Lambda(1520)$  (there emerged some hints after the conference that this might indeed be the case[25])

However, it may be premature to seek radical solutions given the nature of the current evidence[24]. The most immediate concern must be to establish not simply the spin and parity of the  $\Theta$ , or other examples like it, but to verify that it indeed exists and is not some combination of statistical fluctuations, some complex novel dynamical background effect that has been overlooked, or psychological desire to be attracted by small positive signals while arguing away any compensating negative results. In the immediate term, a dedicated high statistics experiment involving photoproduction at Jefferson Laboratory, planned to take data in 2004 may help to settle some of these questions.

Whether or not it turns out to be real, the stimulus to theory has already reinvigorated interest in the Skyrme model (which even predicted that such a state should exist, at such a mass, though admittedly not with a width so small) and the pentaquark dynamics of the quark model. The Skyrme model and the quark model are both rooted in QCD though their relation has been obscure. Considerable theoretical attention into their relation has been stimulated by the  $\Theta$  studies. (Following the conference there has appeared a paper which suggests[34] that the exotic  $\Theta$  is an artifact of the rigid rotator approach to the Skyrme model, and that in the  $SU(3)_F$  limit the  $\bar{\mathbf{10}}$  does not form. )

Skyrme's model, when extended to incorporate strangeness, implied that the lightest baryon families consisted of  $(\mathbf{8}_{\frac{1}{2}}^{1+})$  which includes the nucleons, and a  $(\mathbf{10}_{\frac{3}{2}}^{3+})$  which includes the  $\Delta, \Omega^-$ . This far its predicted pattern is like that of the quark model based on three quarks interacting with QCD forces and also as seen in the data. However, it was noticed that in this Skyrme model, there is a further family of ten (transforming like a "ten-bar", of  $SU(3)$ -flavour) with  $J^P = \frac{1}{2}^+$ . This is the family that can not be formed from three quarks and requires the pentaquark as a minimum configuration.

Initially it was thought that the pentaquark would lead to negative parity for the lightest states, in contradiction to the Skyrme model prediction of positive parity. However, the color magnetic forces of QCD, when combined with constraints on flavor and spin required by fundamental symmetries (such as Bose symmetry and the Pauli exclusion principle) cause the lightest observable states plausibly to contain one unit of internal angular momentum and thereby have positive parity [29, 28].

However, there does appear to be a significant potential difference between the models, which should be experimentally testable. Both predict that there are two further exotic members of the "ten-bar" family: they have strangeness minus two, like the familiar  $\Xi$  baryons, but whereas the familiar  $\Xi$  states have electric charges 0 or -1, these can have 0, -1 and also +1 or -2. Positively charged or doubly negatively charged baryons with strangeness minus two are hitherto unknown.

And this is where the potential difference arises. In the formulation of the Skyrme model for broken  $SU(3)$  in[27], the mass gap between the  $\Theta$  and these  $\Xi$  has to be **larger** than that in the conventional ten, spanned by the  $\Delta(1236)$  and  $\Omega^-(1672)$ . This appears to be unavoidable if the  $\bar{\mathbf{10}}$  masses are to be above those of the familiar decuplet. Indeed, they predicted this gap in the "ten-bar" to be some 540MeV leading to a mass for the  $\Xi$



exceeding 2GeV. In the pentaquark picture, by contrast, one need only pay the price for one extra strange mass throughout the  $\bar{\mathbf{10}}$ . This implies a relatively light mass for the  $\Xi \sim 1700\text{MeV}$  with the possibility that these states also could be relatively stable.

I will now describe the wavefunctions of the pentaquark in more detail to show that there is **no** simple mapping onto the Skyrme model as initially presented in [27].

## $\bar{\mathbf{10}}$ Wavefunctions

To get a feeling for a  $\bar{\mathbf{10}}$ , first recall the most familiar decuplet of baryons. This forms a large inverted triangle with the  $\Omega^-$  at its pointed base and  $\Delta^{++}; \Delta^-$  at the two extremes of its "shoulders"; the strangeness spans 0 to -3. Now consider the corresponding antibaryons, making a  $\bar{\mathbf{10}}$ . Now we will have the (anti- $\Omega$ ) $^+$  at the pointed head of the triangle and (anti- $\Delta$ ) $^{--}$  and (anti- $\Delta$ ) $^+$  at the extremes of its base; the strangeness spans +3 to 0. Note the electric charges of these states. The  $\bar{\mathbf{10}}$  of interest in the present story is like this but with the magnitudes of strangeness being two units less throughout than the antibaryon one just described. Thus instead of the (anti- $\Omega$ ) $^+$  ( $S = 3$ ) at the pointed head of the triangle we have  $\Theta^+$  ( $S=1$ ). In place of the (anti- $\Delta$ ) $^{--}$  and (anti- $\Delta$ ) $^+$  ( $S = 0$ ) at the extremes of its base we have the exotic ( $S = -2$ )  $\Xi^{--}; \Xi^+$ .

Thus we see the presence of three exotic correlations of strangeness and charge. The  $\Theta^+$  is what is claimed to have been discovered; the  $\Xi^{--}; \Xi^+$  are a remaining challenge.

We all know how to write the wavefunctions for a  $\bar{\mathbf{10}}$  made of three antiquarks. However, there appears to be some confusion about the analogous wavefunctions for a  $\bar{\mathbf{10}}$  made of pentaquarks. In particular the form quoted in the discussion session here is not a  $\bar{\mathbf{10}}$ . Given this confusion I will describe here in a heuristic way, how to build them. This will immediately expose essential differences with the Skyrme model and suggest further novel implications in the baryon spectrum.

I am going to view the  $qqqq\bar{q}$  as two diquarks  $qq$ - $qq$  accompanying an antiquark. To form the wavefunctions and take care of their symmetries note first how the diquarks transform under  $SU(3)_f$ . Define the antisymmetric diquark states cyclically under  $u \rightarrow d \rightarrow s$  so that (apart from normalisations)

$$(ud) \equiv (ud - du) \rightarrow \bar{s}; (ds) \equiv (ds - sd) \rightarrow \bar{u}; (su) \equiv (su - us) \rightarrow \bar{d}$$

Then take the traditional wavefunctions for antibaryons, retain one antiquark and replace the others by the corresponding diquark.

The  $\Theta$  state  $(ud)^2\bar{s}$  is thus seen immediately to be symmetric and analogous to the  $\bar{\Omega}^+$ . The analogues of the  $\bar{\Delta}^{--}$  and  $\bar{\Delta}^+$  are then respectively  $(ds)^2\bar{u}$  and  $(su)^2\bar{d}$ . These form  $\Xi$  states with strangeness = -2 in our  $\bar{\mathbf{10}}$ .

Before writing wavefunctions note immediately that there is only **one** extra strange mass in the  $\Xi$  states relative to the  $\Theta$ . Thus in the pentaquark model one necessarily has low lying exotic  $\Xi$  states around 1700MeV if one identifies the  $\Theta(1540)$  to set the scale. This is different from the Skyrme model as originally presented in [27].

This is an important fact worthy of some comment in view of the prediction[27] of the  $\Theta$  in a  $\bar{\mathbf{10}}$  in a version of the Skyrme model. However, it was critical in that prediction that the mass gap from  $\Theta$  to  $\Xi$  is **three** units of  $\Delta(m_s - m_d) \sim 150\text{MeV}$ , as for the conventional

(anti)decuplet of (anti) $\Delta$  – (anti) $\Omega$ . In a pentaquark picture the mass gap is only a single unit.

The difference comes from the way that [27] implemented flavour symmetry breaking. A crucial assumption was that the SU(3) breaking for  $m_s \neq m_d$  depends linearly on the hypercharge  $Y=B+S$  such that  $M(Y) = M_0 - cY$  where  $c > 0$ . For the familiar baryon  $\mathbf{10}$  this is equivalent to counting the number of strange quarks. However, this is not a general axiom. It does not work for mesons, for example, where  $m(K^+) \equiv m(K^-)$  and  $m(\omega) < m(\phi)$ , nor for the octet baryons where  $m(\Sigma) > m(\Lambda)$ . The origin of these masses are immediately obvious in the quark model with hyperfine interactions.

The reason for the difference is that  $s$  and  $\bar{s}$  contribute equally to the strange mass content, but cancel out in the hypercharge. In the  $\bar{\mathbf{10}}$  of interest here, the simple correspondence familiar in the non-exotic  $\mathbf{10}$  is lost. The mass gap from shoulder to toe of the 10, or from tip to base of the pyramid in the  $\bar{\mathbf{10}}$  is given by the difference in **moduli** of the respective strangeness. Thus for the familiar 10 or  $\mathbf{10}$  which run from strangeness 0 to  $\pm 3$  we have **three** units of strange mass, whereas for the case here which runs from strangeness +1 to -2 the modular difference is only one.

Ref.[27] forced the interval between the Theta and the N to be 1710-1540=170MeV and thereby inflate the mass splittings. As we already commented, the mass gap is  $\frac{1}{3}m_s$  per stage in the  $\bar{\mathbf{10}}$  for the pentaquark whereas ref[27] chose numbers with more like one  $m_s$  per unit gap. Now their model at first sight appears to hide beneath parameters  $\alpha\beta\gamma$  (eq 16-18 in hep-ph/9703373). However, this is not really so. Critical is the mass gap per unit of strangeness in table 1 of ref.[27] which gives the mass gaps per unit strangeness to be  $1/8\alpha + \beta - 5/16\gamma$  for normal 10 and  $1/8\alpha + \beta - 1/16\gamma$  for the novel  $\bar{\mathbf{10}}$ . Hence in their convention where  $1/8\alpha + \beta < 0$  then if  $\gamma < 0$  (see later) the mass gap per unit of strangeness in their  $\bar{\mathbf{10}}$  must be **BIGGER** than in the conventional 10. The only way to get it smaller, as in the pentaquark picture would be for  $\gamma > 0$ .

So, what can one say about  $\gamma$  in general?

First see eq 18 of ref[27] and the comment at end of section 2: “ $I_1 > I_2$  so that the  $\bar{\mathbf{10}}$  is heavier than the familiar decuplet”. This tends to force  $\gamma$  negative and toward  $2\beta/3$  (which is indeed in accord with their actual numbers of  $\gamma \sim -107\text{MeV}$  and  $\beta \sim -156\text{MeV}$  in their eq 27). So there appears to be an inherent distinction between the Skyrme picture of [27] and the pentaquark, so long as  $m(\bar{\mathbf{10}}) > m(\mathbf{10})$ .

There are other differences between the two pictures. To motivate these, we need first to look more carefully at the wavefunctions for the other states in the multiplet. The wavefunctions can be obtained by applying the U-spin lowering operator to the  $\Theta$ .  $U_-$  changes  $d \rightarrow s$  or  $\bar{s} \rightarrow -\bar{d}$ .  $U_-$  commutes with the Casimir operators of SU(3), and so under its operation one remains in the  $\bar{\mathbf{10}}$ . Thus for example

$$|p\rangle = \frac{1}{2\sqrt{3}} \left( [(ud - du)(su - us) + (su - us)(ud - du)]\bar{s} + (ud - du)^2\bar{d} \right)$$

or more succinctly

$$p = -\sqrt{\frac{2}{3}} [(ud)(su)_+] \bar{s} - \sqrt{\frac{1}{3}} (ud)^2 \bar{d}$$

We can expose the hidden  $s\bar{s}$  or  $d\bar{d}$  heuristically, though at the expense of suppressing the above symmetries, by writing this in the “shorthand” form

$$p(\bar{\mathbf{10}}) = uud \left( \sqrt{1/3} |d\bar{d}\rangle + \sqrt{2/3} |s\bar{s}\rangle \right).$$

In similar fashion

$$|\Sigma^+(\bar{\mathbf{10}})\rangle = U_- |p\rangle \rightarrow uus \left( \sqrt{2/3} |d\bar{d}\rangle + \sqrt{1/3} |s\bar{s}\rangle \right)$$

These are like familiar baryons with extra hidden strangeness or hidden  $d\bar{d}$  in a specific weighted combination for the  $\bar{\mathbf{10}}$ . This immediately allows one to count the total number of  $s + \bar{s}$  in each state. In the  $N$ , for example, you get:  $(1/3) \times (0) + (2/3) \times 2 = 4/3$ . For the  $\Sigma$ :  $(2/3) \times 1 + (1/3) \times 3 = 5/3$ . Hence one sees explicitly the equal mass rule but with  $m_s/3$  per unit change of strangeness, consistent with our earlier observation that the total mass interval between the  $\Theta$  and the  $\Xi^+ \equiv -(us)^2\bar{d}$  feels only **one** extra strange contribution.

Now we come to the interesting features, namely those states that are not at the corners of the  $\bar{\mathbf{10}}$ . These can also form octet representations, whose wavefunctions are orthogonal to the above; they are

$$p(\mathbf{8}) \rightarrow uud \left( \sqrt{2/3} |d\bar{d}\rangle - \sqrt{1/3} |s\bar{s}\rangle \right) \quad (1)$$

$$\Sigma^+(\mathbf{8}) \rightarrow uus \left( \sqrt{1/3} |d\bar{d}\rangle - \sqrt{2/3} |s\bar{s}\rangle \right) \quad (2)$$

Counting the number of  $s + \bar{s}$  one gets for the relative strange mass content to the mass pattern in the octet  $N : \Sigma : \Xi = 2/3 : 7/3 : 2$ .

Photoproduction of the  $\bar{\mathbf{10}}$  is interesting since the photon has  $U = 0$  and so cannot cause transition from  $p(\mathbf{8})(U = 1/2)$  to  $p(\bar{\mathbf{10}})(U = 3/2)$ . By contrast, the neutron is in a  $U = 1$  multiplet for both  $\mathbf{8}$  and  $\bar{\mathbf{10}}$ , and hence  $\gamma n(\mathbf{8}) \rightarrow \bar{\mathbf{10}}$  is allowed. To see this with the above wavefunctions, let the photon convert to a  $q\bar{q}$  with amplitude proportional to the charge  $e_q$ ; form the transition amplitude by isolating the terms in the  $\bar{\mathbf{10}}$  wavefunction where  $(q_i q_j)(q_k q_l)\bar{q}_l$  occur with the  $q$  and  $\bar{q}$  of the same flavour adjacent to one another. Thus

$$p \rightarrow (ud - du)u [s\bar{s} - d\bar{d}]$$

exposes the coupling to the mixed-antisymmetric conventional octet proton  $uud$  state, and a  $U = 1$  state. This explicitly shows that  $p(\mathbf{8}) \rightarrow p(\bar{\mathbf{10}})$  transforms as  $\Delta U = 1$  whereby photoproduction is forbidden.

The analogous exercise for a neutron gives

$$n \rightarrow (ud - du)d [s\bar{s} - u\bar{u}]$$

where the  $q\bar{q}$  piece now transforms as  $V = 1$ , or equivalently as a linear superposition of  $I = 1$  and  $U = 0$ . The latter therefore allows  $\gamma n(\mathbf{8}) \rightarrow \bar{\mathbf{10}}$ .

Thus photoproduction could be imagined as a way to distinguish whether the pentaquark  $p^*$  is in  $\mathbf{8}$  or  $\bar{\mathbf{10}}$ . However, it is at this point, if not already, that one realises that the language of  $\bar{\mathbf{10}}$  and  $\mathbf{8}$  is not really suitable. The symmetry breaking allows mixing between the two multiplets and depending on the dynamics this may tend toward the extreme which respectively maximises and minimises the net  $s + \bar{s}$  content. Thus the mass eigenstates may be expected to tend toward the following (subscripts L and H for light and heavy):

$$N_L = (ud)^2 \bar{d}; N_H = (ud)(us) \bar{s}$$

and

$$\Sigma_L = (ud)(ds) \bar{u}; \Sigma_H = (ds)^2 \bar{s}$$

In this case we see that for the set of "light" states, there is an increase of order  $m_s$  per strange gap, while the same is true for their heavy counterparts until the final stage where the  $\Xi$  is lighter than the  $\Sigma$ , thereby preserving the ubiquitous rule that there is only one unit of "extra" strange mass between  $\Theta$  and  $\Xi$ .

Thus if one identifies the  $m(\Theta) \sim 1540\text{MeV}$ , one might identify  $m(N_H) \sim 1710$  (contrast the Skyrme model which identified the  $\bar{\mathbf{10}}$  with this state) and then have the prediction of a lighter state, perhaps  $m(N_L) \sim 1400\text{MeV}$ , which could be related to the Roper resonance[29].

In the Skyrme model the  $\bar{\mathbf{10}}$  has  $J^P = \frac{1}{2}^+$ ; there is no accompanying octet, and hence no possibility of mixing. In the pentaquark model one might naively expect that the lowest lying states are  $J^P = \frac{1}{2}^-$ ; however, when the interquark QCD spin dependent forces are taken into account one finds[29, 28] that octet and  $\bar{\mathbf{10}}$  emerge lightest with  $J^P = \frac{1}{2}^+$ . However, one also finds that they are partnered by  $J^P = \frac{3}{2}^+$  multiplets too. Let's now look into this and assess experimental tests.

### *Diquark Cluster Models*

Early evidence that mesons and baryons are made of the same quarks was provided by the remarkable successes of the Sakharov-Zeldovich constituent quark model, in which static properties and low lying excitations of both mesons and baryons are described as simple composites of asymptotically free quasiparticles with a flavor dependent linear mass term and hyperfine interaction,

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{ij}^{hyp} \quad (3)$$

where  $m_i$  is the effective mass of quark  $i$ ,  $\vec{\sigma}_i$  is a quark spin operator and  $v_{ij}^{hyp}$  is a hyperfine interaction.

As first pointed out by Karliner and Lipkin[28], a single-cluster description of the  $(uudd\bar{s})$  system fails because of the repulsive interaction between the pairs of the same

flavor, which prevents binding. This leads one to consider dynamical clustering into subsystems of diquarks or/and triquarks, which amplify the attractive color-magnetic forces. There are two routes that emerge naturally; one is that of [28], the other of Jaffe and Wilczek [29]. These naturally lead to  $J^P = \frac{1}{2}^+$  as the lowest mass states.

The first step is common and is based on the strong chromomagnetic attraction between a  $u$  and  $d$  flavour when the  $ud$  diquark is in the  $\bar{3}$  of the color  $SU(3)$  and in the  $\bar{3}$  of the flavor  $SU(3)$  and has  $I = 0, S = 0$ , like the  $ud$  diquark in the  $\Lambda$ .

Such an idea has a long history, being the source of the  $\Lambda - \Sigma$  mass difference, a possible linkage with the dominance of  $u(x \rightarrow 1)$  in deep inelastic structure functions and of the maximisation of the polarisation asymmetry in this same limit. Such attraction between quarks in the color  $\bar{3}$  channel halves their effective charge, reduces the associated field energy and is a basis of color superconductivity in dense quark matter [33]. There is the implied assumption that such a "diquark" may be compact, an effective boson "constituent", which is hard to break-up and hard for its constituents to rearrange with other quarks or antiquarks in the bound state. I shall refer to this by  $[(ud)_0]$ , the subscript denoting its spin, and the  $[ ]$  denoting the compact quasiparticle.

JW consider the following subcluster for the pentaquark:  $[(ud)_0][(ud)_0]\bar{s}$ . KL also start with the  $[(ud)_0]$  seed, but regard the remainder as a strongly bound "triquark"  $[(ud)_1\bar{s}]$ . This internal structure is chosen to give the minimum energy to the triquark system; the  $(ud)_1$  is coupled to spin 1, colour 6; the  $\bar{s}$  couples to the  $u$  or the  $d$  to net spin 0. Thus we see there is this difference in details between the two approaches. First I will describe their dynamics and see what consequences there are.

For JW the two  $(ud)$  must combine to make  $3_c$  in order to neutralise the  $\bar{s} = \bar{3}$ ; since  $\bar{3} \times \bar{3} \rightarrow 3$  is antisymmetric in colour, and since the  $(ud)_0$  boson pair must be symmetric overall this implies that they are in P-wave (spatially antisymmetric). This gives a negative parity that combines with the negative parity of  $\bar{s}$  to give an overall positive parity system. Thus one has  $J^P = \frac{1}{2}^+; \frac{3}{2}^+$  pentaquark systems. It is possible to identify the mass with the  $\Theta$  (see later); the metastability can be accommodated by insisting that the quasiparticles in  $[(ud)_0][(ud)_0]\bar{s}$  prevent simple rearrangement to overlap with  $[(ddu)][u\bar{s}]$ , which are the  $NK$  colour singlet hadrons.

Whereas JW take the other  $ud$  diquark also to be in this configuration and then put the two diquarks in relative P-wave (by Bose symmetry after the colour is taken account of), KL by contrast took the remaining  $ud\bar{s}$  and looked for the configuration in color and spin which would optimize the total (five-body) hyperfine interaction.

Karliner and Lipkin divide the system into two color non-singlet clusters which separate the pairs of identical flavor. The two clusters, a  $ud$  diquark and a  $ud\bar{s}$  triquark, are separated by a distance larger than the range of the color-magnetic force and are kept together by the color electric force. Therefore the color hyperfine interaction operates only within each cluster, but is not felt between the clusters. They associate the  $[(ud)_0]$  with the non-strange piece of the  $\Lambda(1110)$  baryon.

Within the  $[(ud)_1\bar{s}]$  the strange subsystems  $u\bar{s}$  and  $d\bar{s}$  are assumed to be in spin 0, by colour-spin forces analogous to the way that the  $K$  is lighter than  $K^*$ . If the diquark and triquark are in relative S-wave, then the colour attractions act among all the constituents leading to a freeze out that would be a  $KN$  S-wave system. In P-wave, the two separate quasi-particles avoid the contact hyperfine forces (their generalisations to the Fermi-

Breit effects are not discussed). These identifications help them to argue that the mass of the system agrees with that of the  $\Theta$ . Analogous to JW, the metastability can be accommodated by insisting that the quasiparticles in  $[(ud)_0][(ud)_1\bar{s}]$  prevent simple rearrangement to overlap with  $[(ddu)][u\bar{s}]$ , which are the  $NK$  colour singlet hadrons.

KL consider also heavy analogues  $[(ud)_0][(ud)_1\bar{Q}]$  where  $Q \equiv s; c; b$ . They do not consider  $Q \equiv u, d$ , possibly because this enables annihilation with the like-flavoured quark in the triquark, thereby destroying the stability and overlapping with conventional  $udu$  or  $udd$  baryons. However, we shall see that such states can have non-trivial consequences.

JW do consider  $[(ud)_0][(ud)_0\bar{Q}]$  with  $Q \equiv u, d$ . The dynamical difference is that the quasi-particle nature of the separate  $[(ud)_0]$  may suppress the annihilation with the like flavour, enabling the states  $[(ud)_0][(ud)_0\bar{Q}]$  with  $Q \equiv u, d$  to have an existence. Such states would be expected to lie  $O(100 - 150)MeV$  below the  $\Theta$ , and they identify them with the Roper  $n; p(1440)$  nucleon resonances.

The mass of the exotic  $\Xi^+$  depends rather sensitively on the effects of clustering. First one needs the effective mass of the diquarks. The mass difference  $m(\Delta) - m(N)$  implies that

$$\Delta m[(ud)_0] = -150MeV; \Delta m[(ud)_1] = +50MeV$$

relative to their mean masses. The strange counterparts follow from  $m(\Sigma^*) - m(\Sigma)$  and implies

$$\Delta m[(us)_0] = -96MeV.$$

Thus

$$\Delta m(\Xi^+ - \Theta^+) = \Delta m(\bar{s} - \bar{d}) + 2\Delta m([(us)_0] - [(ud)_0]) \sim 230 - 250MeV.$$

So 1750-1800MeV is the mass range one obtains with this level of approximation, which is still significantly below the original prediction in ref[27]. There is further uncertainty in estimating the mass in that the orbital excitation of the  $[us][us]$  and  $[ud][ud]$  will have different energetics and the  $\vec{L} \cdot \vec{S}$  shifts are also dependent on the flavours. These could easily add further uncertainties of  $\pm 50MeV$ . If and when the  $\Xi^{+(-)}$  are discovered, along with their  $J^P = \frac{3}{2}^+$  counterparts, their masses will enable the systematics of the clustering to be determined by fitting the above.

## Other pentaquark states

At first sight the narrowness of the  $\Theta$  would seem to argue against any identification of the broad Roper resonance as a nucleon analogue. However, this need not be so. Some of the following thoughts emerged from discussion with Maltman at the conference[35].

For a simple attractive square well potential of range 1fm. the width of a P-wave resonance 100MeV above  $KN$  threshold is of order 200MeV[29, 35]. However, this has not yet taken into account any price for recoupling colour and flavour-spin to overlap the  $(ud)(ud)\bar{s}$  onto colour singlets  $uud$  and  $d\bar{s}$  say for the  $KN$ . In amplitude, starting with

the Jaffe-Wilczek configuration, the colour recoupling costs  $\frac{1}{\sqrt{3}}$  and the flavour-spin to any particular channel (e.g.  $K^+n$ ) costs a further  $\frac{1}{4}$ . This appears to be akin to the factor  $1/2\sqrt{6}$  found in ref[35] for the isospin-spin-colour overlap in their conventions. They go further and consider the mixing with the Karliner-Lipkin configuration gives for the lowest eigenstate a suppression of  $\frac{1}{25}$ [35]. Hence a width of  $O(1 - 10MeV)$  for  $\Theta \rightarrow KN$  may be reasonable.

The decay involves tunneling through the P-wave barrier, which by analogy with  $\alpha$ -decay is exponentially sensitive to the difference between the barrier height and the kinetic energy of the state. This can affect the width of a spin  $\frac{3}{2}$  “ $\Theta^*$ ” partner, whose mass  $> m(\Theta)$ , arising from the  $\vec{L} \cdot \vec{S}$  splitting effects in the pentaquark system. This splitting is model dependent[36] but might be as small as  $\sim 30 - 80MeV$ . Given the exponential sensitivity in a tunneling width, the  $\Theta^*$  could be high enough in the well to be broad. In any event such a state should be sought. If the above is a guide, only  $\Theta^* \rightarrow \Theta\gamma$  is kinematically allowed as a transition. If its mass exceeds 1820MeV it becomes possible for a strong decay width  $\Theta^* \rightarrow \Theta\pi\pi$  to feed at least some of the  $\Theta$  signal.

The exponential sensitivity could frustrate attempts to differentiate between the pentaquarks and (original) Skyrme model in connection with the exotic  $\Xi$  states. In Skyrme these are above 2GeV and relatively broad; in pentaquarks they are  $\sim 1700MeV$  and hence the possibility of being relatively narrow, perhaps only 50% broader than the  $\Theta$ [29]. However, exponential dependence could cause even 1700 MeV to be high enough in the well to give a broad width to  $\Xi\pi$ . It would be galling if the  $\Theta$  were the only sharp state. (See also ref.[34] and comments earlier about the potential non-binding of the **10** in the Skyrme picture.)

For the Roper, the naive mass of the  $uudd\bar{d}$ , by comparison with the  $\Theta$ , would be  $\sim 1400MeV$ . Its physical mass of 1430-1470MeV[37] may therefore have it elevated in the potential, where the exponential behaviour drives its large width. These possibilities need more careful study in models.

However, for the non-exotic states the picture is not so simple. As stressed earlier, there is no absolute meaning to a pentaquark configuration when a  $qqq$  constituent state can carry the same overall quantum numbers. Thus the  $uudd\bar{d}$  is at best the  $SU(3)$  flavour state within the pentaquark wavefunction of the Roper, or for that matter, of the nucleon. Mass eigenstates will be mixtures of  $qqq$ , these pentaquark states and higher configurations. The nucleon may be  $qqq$  in leading order with its pentaquark components, which naively exist at higher mass scale, revealed with increasing  $q^2$ . For the Roper, the mass scales of the pentaquark and the excited  $qqq$  components may compete. Certainly both states require  $qqq$  presence in order to understand the -2:3 relative amplitudes for  $\gamma n : \gamma p$  magnetic moment/transitions. Furthermore, the existence of the  $\Delta(1660)$  as a potential partner of the Roper (analogous to the  $\Delta(1230)$  for the nucleon) plays an essential role in disentangling these states. Improved data on its photo-excitation from Jefferson Laboratory could help here. Note there is no simple place for such a state if the Roper were pure pentaquark.

## The Nucleon Sea

As stressed above: the number of quarks in a nucleon is not a meaningful quantity. As  $q^2$  varies the nucleon's structure is probed on ever finer resolution and the sea of  $q\bar{q}$  is exposed. All that we can say is that three is the minimum number of quarks required to satisfy the overall quantum numbers. Thus there are pentaquark, heptaquark and ad-inf.-quark components to the wavefunction of any state which transforms like a nucleon.

In the case of a positively charged positive strangeness baryon, the  $uudd\bar{s}$  is the minimal configuration compatible. Thus for such a state there is meaning to the pentaquark as the minimum "valence" wavefunction. Within the pentaquark sector, which contains this state, there are configurations which transform like a nucleon and these are in general mixtures of octet and  $\bar{\mathbf{10}}$ , as described above

$$uud [\cos\theta(d\bar{d}) + \sin\theta(s\bar{s})]$$

The QCD forces that have led to the  $\Theta$  being the lightest pentaquark state will lead to the above as the lightest analogues with nucleon quantum numbers. Note in particular that it is the attractive forces between  $ud$  pairs that have favoured these and contrast this with the  $uudu\bar{u}$  pentaquark, which is in a  $\mathbf{27}$  of flavour SU(3), and is pushed to higher energy by the repulsive forces between the symmetric  $u$  quarks.

If indeed the lightest proton excitation is the  $(ud)^2\bar{d}$ , then this would be a natural candidate for the leading piece of the five body proton Fock state. This is of course what the folklore for failure of Gottfried sum rule requires; the asymmetry that leads to the "missing"  $(ud)uu\bar{u}$  in this picture is because the  $\mathbf{27}$  is pushed up relative to the  $\mathbf{10-8}$  mixture. The antiquark sea is also naively polarised "against the flow" too.

There is an interesting duality between this and other interpretations of this flavour asymmetry in the sea. One is to invoke Pauli blocking of the  $u\bar{u}$  due to the extra  $u$  flavour in the valence proton. In effect, this is an essential feature subsumed within the arguments of [29, 28], which addressed the pentaquark configuration for the  $\Theta$ .

Another approach has been to consider the  $N\pi$  cloud of the nucleon. The essence is that  $p \rightarrow n\pi^+(u\bar{d})$  feeds the  $\bar{d}$  whereas the  $\bar{u}$  is energetically disfavoured, requiring  $p \rightarrow \Delta^{++}\pi^-(d\bar{u})$ . The QCD forces that push the  $m(\Delta) > m(n)$  are the same that distorted the pentaquark configurations, favouring the  $\mathbf{8-10}$  over the  $\mathbf{27}$ . So the role of multi-quark configurations, and their mapping onto the meson-baryon sectors, are all pervading. It is a question of approximation as to whether one or other dominates, or whether both play competing roles. Whether the  $\Theta(1540)$  will turn out to be the first real evidence for a state with a minimal pentaquark "valence" configuration, or merely a strange story to tell future generations, it has certainly raised challenging questions and is leading to some unexpected insights.

## Postscript on $\Theta$ for future historians

A vote at the conference on whether  $\Theta$  can be regarded as (i) an established resonance, (ii) jury still out, (iii) is not a resonance, was split approximately  $\frac{1}{4}$ ,  $\frac{1}{2}$  and  $\frac{1}{4}$  respectively. The total number of votes cast was  $O(100)$ . People who were involved in any of the



relevant experiments or had written theory papers on  $\Theta$  were excluded from the vote. There appeared to be a slight tendency for senior experimentalists to vote in category (iii). Whether this is because of experience with the machinations of statistics in the past, or frustration at having overlooked a major discovery, is for psychologists to debate.

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