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Large states beyond $q\bar{q}$ in QCD: From pentaquarks to no quarks

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Abstract. This talk summarises evidence for states beyond those expected in the simple constituent quark model. I focus on the scalar glueball and its mixing with states in the $q\bar{q}$ nonet, and also on correlations in Strong QCD that may form diquarks and seed $qq\bar{q}\bar{q}$ states. Some models of the pentaquark candidate $\Theta(1540)$ are critically discussed.

In the heavy flavour sector there are clearly established scalar mesons $c\bar{c}$ and $b\bar{b}$. They behave as canonical ${}^3P_0$ states which partner ${}^3P_{1,2}$ siblings. Their production (e.g in radiative transitions from 2^3S_1 states) and decays (into 1^3S_1 or light hadrons) are all in accord with this. There is nothing to suggest that there is anything "exotic" about such scalar mesons.

For light flavours too there are clearly identified ${}^3P_{1,2}$ nonets which call for analogous ${}^3P_0$ siblings. However, while all other J^{PC} combinations appear to be realised as expected, (apart from well known and understood anomalies in the 0^{-+} pseudoscalars), the light scalars empirically stand out as singular.

The interpretation of the nature of the lightest scalar mesons has been controversial for over thirty years. There is still no general agreement on where are the $q\bar{q}$ states, whether there is necessarily a glueball among the light scalars, and whether some of the too numerous scalars are multiquark, $K\bar{K}$ or other meson-meson bound states. These are fundamental questions of great importance in particle physics. The mesons with vacuum quantum numbers are known to be crucial for a full understanding of the symmetry breaking mechanisms in QCD, and presumably also for confinement.

Theory and data are now converging that QCD forces are at work but with different dynamics dominating below and above 1GeV/c^2 mass. The experimental proliferation of light scalar mesons is consistent with two nonets, one in the 1 GeV region (a meson-meson nonet) and another one near 1.5 GeV (a $q\bar{q}$ nonet), with evidence for glueball degrees of freedom.

Let's consider the scalar mesons above and then below 1GeV.

No quarks?

Lattice QCD predictions for the mass of the lightest (scalar) glueball are now mature. In the quenched approximation the mass is ~ 1.6GeV [1,2]. Flux tube models imply that if there is a $q\bar{q}$ nonet nearby, with the same J^{PC} as the glueball, then $G - q\bar{q}$ mixing will dominate the decay [3]. This is found more generally [4] and recent studies on coarse-grained lattices appear to confirm that there is indeed significant mixing between G and $q\bar{q}$ together with associated mass shifts, at least for the scalar sector [5].

Furthermore the maturity of the $q\bar{q}$ spectrum tells us that we anticipate the $0^{++}q\bar{q}$ nonet to occur in the 1.2 to 1.6 GeV region: there are candidates
$a_0(\sim 1400); f_0(1370); K(1430); f_0(1500)$ and $f_0(1710)$.

One immediately notes that if all these states are real there is an excess, precisely as would be expected if the glueball predicted by the lattice is mixing in this region. Any such states will have widths and so will mix with a scalar glueball in the same mass range. It turns out that such mixing will lead to three physical isoscalar states with rather characteristic flavour content [2,7]. Specifically: two will have the $n\bar{n}$ and $s\bar{s}$ in phase ("singlet tendency"), their mixings with the glueball having opposite relative phases; the third state will have the $n\bar{n}$ and $s\bar{s}$ out of phase ("octet tendency") with the glueball tending to decouple in the limit of infinite mixing.

$$\left(\begin{array}{cccc} Meson & G & s & n \\ 1710: & + & + & + \\ 1500: & - & + & - \\ 1370: & - & + & + \end{array}\right)$$

There are now clear sightings of prominent scalar resonances $f_0(1500)$ and $f_0(1710)$ and, probably also, $f_0(1370)$. Confirming the resonant status of the latter is one of the critical pieces needed to clinch the proof. The production and decays of these states are in remarkable agreement with this flavour scenario [6,7].

$$\left(\begin{array}{cccc} Meson & G & s & n \\ 1710: & 0.4 & 0.9 & 0.1 \\ 1500: & -0.6 & 0.3 & -0.7 \\ 1370: & -0.7 & 0.15 & 0.7 \end{array}\right)$$

The fact that mass mixing and also meson decays are consistent with this set of relative phases is interesting.

The numerical values should not be taken seriously; the errors on them are probably considerable, but the relative phases and separation of "large, medium, small" is probably reliable. As example, a recent model calculation by [8] finds a similar pattern (their glueball phase is defined opposite to what I used here)

The question now is what experimental tests we can do to test this further.

The suggestion here is to use the ideal mixing of the vector mesons as a flavour filter by studying the radiative decays $0^{++} \to \gamma(\rho;\omega;\phi)$. The transitions to ρ and ϕ respectively weigh the $n\bar{n}$ and $s\bar{s}$ content of the initial states. The problem has been that radiative decays have small branching ratios, $\sim 1\%$, and there has not been a reliable source of a large number of scalar mesons with which we can study the radiative decays. This is now about to change. At BES in Beijing and CLEO-c at Cornell, $e^+e^- \to \psi$ will produce in excess of a billion ψ. Their radiative decays to individual $C = +$ mesons, $\psi \to \gamma M$ are typically of order 10^{-3}, giving a million events per meson. Even with a pessimistic branching ratio of $\sim 10^{-3}$ for the subsequent radiative decay $M \to \gamma V(= \rho;\phi)$, given the promised excess of a billion ψ decays, we may hope for over a thousand events per channel and the ability to "weigh" the flavour contents. This can be applied to any C=+ meson produced in $\psi \to \gamma M$.

This mixing scenario may have significant implications for the pattern of states seen in $\psi \to M_1 M_2$ for meson pairs. The traditional idea has been that production of of ϕ or ω in ψ hadronic decays acts as a flavour filter, thus $\psi \to \phi M(s\bar{s})$ and $\psi \to \omega M(n\bar{n})$. Thus it has been a surprise that BES find the scalar mesons $f_0(1370;1500;1710)$ produced against ϕ and ω in a pattern that does not easily fit with this [9]. For example the $f_0(1370)$ is seen in $\psi \to \phi\pi\pi$ and $\phi K\bar{K}$ but not in $\omega\pi\pi$. However, this does not take account of the additional contribution that arises from glueball production $\psi \to \phi G$ [10]. With the mixing pattern as in the matrices above, we can impose a destructive interference between the glueball and $n\bar{n}$ components of the wavefunction of the $f_0(1370)$ in the ωM cases; the small $s\bar{s}$ component does not kill the glueball component in the ϕM case, hence the presence of the $f_0(1370)$ here. Having adopted this convention, one is forced to a pattern of the other scalar mesons recoiling against ω or ϕ. This seems qualitatively to agree with the emerging BES data but much better statistics are required if this is to be tested definitively.

Diquarks and tetraquarks

As pointed out by Jaffe [11] long ago, there is a strong QCD attraction among qq and $\bar{q}\bar{q}$ in S-wave, 0^{++}, whereby a low lying nonet of scalars may be expected. As far as the quantum numbers are concerned these states will be like two 0^{-+} $q\bar{q}$ mesons in S-wave. In the latter spirit, Isgur and Weinstein [12] had noticed that they could motivate an attraction among such mesons, to the extent that the $f_0(980)$ and $a_0(980)$ could be interpreted as $K\bar{K}$ molecules.

The relationship between these is being debated [13] but while the details remain to be settled, there is a rather compelling message of the data as follows [14]. Below 1 GeV the phenomena point clearly towards an S-wave attraction among two quarks and two antiquarks (either as $(qq)^{\bar{3}}(\bar{q}\bar{q})^3$, or $(q\bar{q})^1(q\bar{q})^1$ where superscripts denote their colour state), while above 1 GeV it is the P-wave $q\bar{q}$ that is manifested. There is a critical distinction between them: the "ideal" flavour pattern of a $q\bar{q}$ nonet on the one hand, and of a $qq\bar{q}\bar{q}$ or meson-meson nonet on the other, are radically different; in effect they are flavoured inversions of one another. Thus whereas the former has a single $s\bar{s}$ heaviest, with strange in the middle and and I=0; I=1 set lightest ("$\phi;K;\omega,\rho$-like"), the latter has the I=0; I=1 set heaviest ($K\bar{K};\pi\eta$ or $s\bar{s}(u\bar{u} \pm d\bar{d})$) with strange in the middle and an isolated I=0 lightest ($\pi\pi$ or $u\bar{u}d\bar{d}$) [11,12].

The phenomenology of the 0^{++} sector appears to exhibit both of these patterns with $\sim$ 1GeV being the critical threshold [14]. Below 1 GeV the inverted structure of the four quark dynamics in S-wave is revealed with $f_0(980);a_0(980)$; κ and σ as the labels. One can debate whether these are truly resonant or instead are the effects of attractive long-range $t-$channel dynamics between the colour singlet 0^{-+} $K\bar{K};K\pi;\pi\pi$, but the systematics of the underlying dynamics seems clear.

As concerns the region below 1GeV, the debate centres on whether the phenomena are truly resonant or driven by attractive t-channel exchanges, and if the former, whether they are molecules or $qq\bar{q}\bar{q}$. The phenomena are consistent with a strong attraction of QCD in the scalar S-wave nonet channels. The difference between molecules and compact $qq\bar{q}\bar{q}$ will be revealed in the tendency for the former to decay into a single dominant channel - the molecular constituents - while the latter will feed a range of channels driven by the flavour spin clebsch gordans. For the light scalars it has its analogue in the production characteristics.

The picture that is now emerging from both phenomenology [7,15,16] and theory [17] is that both components are present. As concerns the theory [17], think for example of the two component picture as two channels. One, the quarkish channel (QQ) is somehow associated with the $(qq)_{\bar{3}}(\bar{q}\bar{q})_3$ coupling of a two quark-two antiquark system, and is where the attraction comes from. The other, the meson-meson channel (MM) could be completely passive (eg, no potential at all). There is some off diagonal potential which flips that system from the QQ channel to MM. The way the object appears to experiment depends on the strength of the attraction in the QQ channel and the strength of the off-diagonal potential. The nearness of the f_0 and a_0 to $K\bar{K}$ threshold suggests that the QQ component cannot be too dominant, but the fact that there is an attraction at all means that the QQ component cannot be negligible. So in this line of argument, a_0 and f_0 must be superpositions of four-quark states and $K\bar{K}$ molecules.

Heavy tetraquarks

There are hints that tetraquark (diquark - antidiquark) systems occur involving heavy flavours. In the charmonium sector we have $X(3871.8)$ seen as a narrow state decaying into $\psi\pi\pi$. Being narrow yet above $D\bar{D}$ threshold suggests that it is forbidden to decay into $D\bar{D}$. This could occur if it is a hybrid charmonium, though the mass scale for these is expected to be somewhat above 4 GeV. More directly, it would be forbidden if its J^{PC} were any of $0^{-+}, 2^{--}, 2^{-+}, 3^{--}$ among others; I have isolated these as they could a priori be among the missing states of charmonium. Unfortunately, or tantalisingly, each of these runs into problems with other data. Their masses are wrong, or their electromagnetic widths or angular distributions do not fit with those expected for such charmonium states [18].

The conclusion is either that the quark model description of charmonium has been exposed as a fraud, or that the state is not simply charmonium. The latter is suspected to be the case in part driven by the remarkable coincidence between its mass and that of the threshold for D^0D^{0*} which agree to better than one part in 10,000. [19,20] suggest that it is a molecular or tetraquark bound state of these mesons in S-wave; thus 1^{++}.

Indirect support for this comes from the fact that such a state is not an isospin eigenstate and so the decays would violate isospin radically. The decay to $\psi\pi\pi$ would have the $\pi\pi$ forming a ρ and not a σ; the very limited data are consistent with this. This 1^{++} assignment is supported by the observation of $\psi\omega$ decay [21]; the ratio of $\psi\rho : \psi\omega$ will become a sharp test of isospin violation and the molecular interpretation. Further tests include verifying that there is no $\psi\pi^0\pi^0$, which would be forbidden for the ρ but allowed for σ. Also the hadronic decays into e.g. $K\bar{K}\pi$ will be dominated by neutral $K^0\bar{K}^0\pi$ relative to $K^+K^-\pi$.

Pentaquarks and exotic baryons

The original conception of the constituent quark model, and of our modern picture, was based on the observation that hadrons exist with (apparently) unlimited amounts of spin, but with only very restricted amounts of electric charge and strangeness. In particular, all baryons seen hitherto in 60 years of research carry either no strangeness (like the proton and neutron) or **negative** amounts (like the Λ, Σ and Ω^-).

During 2003 evidence emerged from a range of experiments that a metastable particle known as the theta baryon may exist [22,24,23,25,26]. Described most simply: it is like a heavier version of the proton but which possesses **positive** strangeness in addition to its positive electrical charge and it is denoted as Θ^+. This makes it utterly novel. As the absence of “positive strangeness baryons” in part is what helped establish the quark model in the first place, the claims are indeed radical.

QCD allows more complicated clusters of quarks or antiquarks and there is good evidence for this. For example, 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 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; in this case the positive strangeness could only be produced by the presence of a strange-antiquark $\bar{s}$, the overall baryon number requiring four further quarks to accompany it. Thus we would have three quarks accompanied by an additional quark and antiquark, making what is known as a “pentaquark”.

The existence of such a state is not of itself necessarily radical; it is the light mass and, most dramatically, its narrow width that tantalise. The challenge is to explain why such a “pentaquark” has such unexpected metastability: whereas conventional hadrons that decay by the action of strong forces have widths of order of hundreds of MeV, that of the Θ^+ is less than 10MeV, perhaps no more than 1MeV if consistency is to be maintained with phase shift analyses of extensive data on the interactions of kaons and nucleons.

There may be a sense of deja-vu here in that strange particles were so called, because of their strange behaviour: they were produced readily in strong interactions, but had metastability due to their decays being controlled by the weak interaction. Thus one suggestion has been that the Θ is but one of a family of particles, each with positive strangeness but with electrical charges that span the range from +3 to -1; such a family with a mass around 1550 MeV would be too light to decay by the strong interactions as all isospin conserving pathways would be forbidden by energy conservation, leaving the weak interaction to cause their decays.

However, to date there is no sight of states such as Θ^{++} that are isospin partners of the Θ^+. The most immediate concern must be to establish not simply the spin and parity of the Θ, or other examples like it, but to verify that it indeed exists and is not some artefact. A programme of photoproduction at Jefferson Laboratory may begin to answer some of these questions.

Whether or not it turns out to be real, the stimulus to theory has already reinvigorated interest in the chiral soliton and Skyrme models (which even predicted that such a state should exist, at such a mass) and the pentaquark dynamics of the quark model. The chiral soliton model and the quark model are both rooted in QCD though their relation has been obscure.

When the chiral soliton model is extended to incorporate strangeness, the lightest baryon families consist of the well established **8** with $J^P = 1/2^+$ (which includes the nucleons) and a **10** with $J^P = 3/2^+$ (which includes the Δ and Ω^-) and a further family of ten (technically transforming like a $\mathbf{\overline{10}}$, in the group structure of SU(3)) with spin parity $1/2^+$. This is the family that can not be formed from three quarks and requires the pentaquark as a minimum. By identifying the members of this $\mathbf{\overline{10}}$ with nucleon quantum numbers with the $P_{11}(1710)$ (which is itself surprising as such a state is forbidden by U-spin to be photoexcited from a proton, in contradiction to data [27]), ref [28] predicted a mass of $\sim$ 1540MeV for the strangeness +1 Θ.

Initially it was thought that in a quark model description of pentaquarks, the lightest states would have negative parity, in contradiction to the chiral soliton model prediction, above, of positive parity. However, it has been realised that 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. Models which assume there is a flavour-spin force within hadrons naturally lead to attractions in baryon states that are flavour-spin symmetric. This might have some role in making the multiplet containing the $P_{11}(1440)$ be lighter than the negative parity baryons which would otherwise be expected in the quark model to have been the lightest excitations of the nucleon. Such forces are attractive for the four quarks within a $\mathbf{\bar{10}}$. The overall Pauli statistics then force a unit of angular momentum into the system leading to overall positive parity.

However, there do appear to be significant potential differences between the models, which should be experimentally testable. Both chiral soliton and pentaquark models predict that there are two further exotic members of the $\mathbf{\bar{10}}$ family: they have strangeness minus two, like the familiar Ξ baryons, but whereas the familiar Ξ 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. In the original chiral soliton model [28], the mass gap between the Θ and these Ξ has to be **larger** than that in the conventional ten, spanned by the $\Delta(1236)$ and $\Omega^-(1672)$. Indeed, ref [28] predicted this gap in the $\mathbf{\bar{10}}$ to be over 500MeV leading to a mass for the Ξ exceeding 2GeV. In the pentaquark picture, by contrast, one need only pay the price for one extra strange mass throughout the ten-bar. This implies a relatively light mass for the $\Xi \sim 1700$MeV with the possibility that these states also could be relatively stable.

Further differences emerge for the first excited states. In the pentaquark models these have $J^P = 3/2^+$ arising from the spin-orbit forces that split the $L = 1 \otimes S = 1/2 \rightarrow J = 1/2 \oplus 3/2$ and will again be $\mathbf{\bar{10}}$. Such a multiplet does not occur in the chiral soliton models. These allow $J^P = 3/2^+$ but in higher dimensions such as **27,35**, in which case the excited partner of the Θ can occur only in a range of charge states. In pentaquark models, such configurations also are possible, but it is only in such models that the excited $J^P = 3/2^+ \mathbf{\bar{10}}$ also occurs.

If narrow width pentaquarks exist with positive parity, this implies there are strong correlations at work in the strong QCD sector. Two particular models that build on this are those of refs. [29,30]. In QCD there are strong attractions between distinct flavours in net spin zero. This is the starting point of these correlated models. It has not been demonstrated how scalar diquarks form with ultra-light masses as required to accomodate a 1540 MeV state; their stability is an open question; their effective boson nature and consistency with hadron spectroscopy also need better understanding. But first we need to establish whether this state is real before getting in too deep. I shall now review various features.

Mass

The original prediction [28] assumed that the 1710 N^* is in the $\bar{10}$ and used this to set the scale of mass. However $\gamma p \rightarrow p^*(\bar{10})$ is forbidden by U-spin which argues against this. The mass gap of 180MeV per unit of strangeness is also suspect in a quark model interpretation as it leads to a 540MeV spread across the $\Theta - \Xi$ multiplet even though there is only one extra strange mass in going from $(udud\bar{s})$ to $(usus\bar{d})$ and so a much smaller gap would be anticipated [29]. Beware the naive application of Gell Mann Okubo mass formulae which do not distinguish between $|S|$ and S as one goes from $\Theta(S = +1)$ to $\Xi(S = -2)$.

If the Θ should prove to be real, then no simple mapping from chiral soliton onto a pentaquark description seems feasible. The relation between these is more profound.

Nonetheless a narrow state of mass $\sim$1540MeV has been claimed. But when one compares the masses reported in K^+n versus K^0p there appears to be a tantalising trend towards a difference [31]. Is this a hint of an explanation (see later) or that we are being fooled by poor statistics?

No models successfully predict the mass; in all cases it is fitted relative to some other assumed measure. The original chiral soliton normalised to the 1710, as we already discussed. [29] assume that the Roper 1440 is the $udud\bar{d}$ (but this state is partnered by $\Delta(1660)$ which along with its electromagnetic and other properties, is in accord with it being a radial qqq excitation of the nucleon). [30] noted the kinematic similarity between reduced masses in their diquark-triquark model and the $c\bar{s}$ system. They adopted a 200MeV orbital excitation energy from the $1^- - 0^+(2317)$ mass gap to realise a 1540MeV mass for the Θ. However, if one makes a spin averaged mass for the $L = 0, 1$ levels, notwithstanding the questions about the low mass of the 2317, one gets nearer to a 450 -480MeV energy gap; this would lead to a Θ nearer 1800 MeV. In summary, all models appear to normalise to some feature and do not naturally explain the low mass of an orbitally excited pentaquark.

Width

The chiral soliton model Lagrangian contains three terms with arbitrary strengths, A, B, C. Linear combinations of these can be related to the observable transition $\Delta N\pi$ and the F/D ratio for the $NN\pi$ vertex. The ΘNK vertex is then given by $g(\bar{10}) = 1 - B - C$. We thus have one unknown $g(\Theta NK)$ described by another unknown, C. [32] shows the coupling is relatively insensitive to F/D and that it is C that controls $g(\Theta NK)$. In the non relativistic quark model it is argued [28,32] that $F/D = 2/3$ and the absence of $s\bar{s}$ in the nucleon lead to $B = 1/5; C = 4/5$. This has the remarkable implication that $g(\Theta NK) = 0$. If the Θ phenomenon survives then a deeper understanding of this result and its implications would be welcome. It would also raise the challenge of how the Θ is strongly produced.

Phenomenologically it has been suggested that the $\Gamma(\Lambda(1520) \to KN) \sim 7$MeV is a measure for narrow widths. However this is D-wave and phase space limited: the P-wave $\Lambda(1660)$ width is ~ 100MeV. Furthermore in these cases one has to create a $q\bar{q}$ pair to initiate the decay; for the pentaquark one has $qqqq\bar{q}$ and the challenge is to stop its decay. There are no indications in conventional spectroscopy that underpin the narrow width of ~ 1MeV for the Θ.

Colour spin and flavour mismatches between the pentaquark and NK wavefunctions have been proposed to suppress the natural width by factors of 24 [33,34] or even more [35]. However it is easy to overcome these: soft gluon exchange defeats the colour; spin flip costs little and flavour rearrangement can occur. Further there is colour singlet $q\bar{q}$ in relative S-wave within the correlated models of JW and KL [36,37] and their dissociation into NK seems hard to prevent.

Stech et al [38] have suggested that the overlaps of spatial wavefunctions between pentaquark and nucleon may lead to a suppression. However it has not been demonstrated that such is generated dynamically. Dudek has shown [37] that such an effect can arise but this involves taking a non relativistic picture rather literally and the self-consistency of the picture remains to be tested. There is also the question of how a colour $\bar{3}$ diquark is attracted into a tighter (smaller?) configuration than a colour singlet meson.

We almost have a paradox here. The small width implies a feeble coupling to KN. Yet something must couple to it very strongly if its production rate is comparable [9] to those of conventional hadrons. This is an enigma which we must confront.

Production

Several experiments place rather strong limits on the hadroproduction of the Θ [9]. Some are not yet restrictive,e.g. the limit in $\psi \to \Theta\bar{\Theta}$ which is phase space limited or that in ψ' decay where one can claim that there is a big price to pay for creating ten q and $\bar{q}$. So it is possible to wriggle. However on balance it seems to me that the limits in high statistics hadroproduction are impressive. The onus is on supporters to explain them away or find a loophole.

An example of such a loophole [39] asks why signals are in photoproduction but not in hadroproduction. The photon contains $s\bar{s}$ and so may be able to feed the $\bar{s}$ needed to make $\Theta(udud\bar{s})$ in a way not so readily accessible in hadroproduction. Further appeal is made to a CLAS observation that suggests that a narrow N^* at ~ 2.4GeV may be the source of $\Theta + K$. While such a dynamics can be tested by searching for other decay modes, forced by SU(3) [39], there remain problems with this. CLAS see this (statistically insignificant) N^* in π exchange and so the photon does not appear to be essential: why is this object (and its progeny, the Θ) not also made in hadroprodcution if it is made by πN? Second; while a 2.4 GeV N^* may be produced in the 3-5 GeV CLAS experiment, it is kinematically inaccessible in the original SpRING8 experiment and in the earlier CLAS γd. So the source of Θ in this latter pair would still remain to be explained.

Photoproduction has also been suggested as a source of kinematic peaks that fake a Θ [40]. $\gamma N \to a_2/\rho_3 N$ followed by the $K\bar{K}$ decays of these mesons in D/F waves give a forward-backward peaking in the c.m. along the direction of the recoil nucleon. If there were no charge exchange the K^+ and K^- would be equally likely to follow the nucleon and so a kinematically generated peak would be as likely in K^+n as in K^-n. The experimental absence of such peaks in K^-n has been cited as support for the reality of the peak in K^+n. However it is not necessarily so simple. Charge exchange introduces a charge asymmetry and it is claimed to be possible to choose phases such that a narrow peak can arise in K^+n (after feeding through Monte Carlo) whereas a broad structure would arise in K^-n. It has been suggested in the discussions that the different Q-values could cause a mass shift in the kinematic peak in K^+n versus K^0p, in accord with the trend of the data noted in [41]. Whether this kinematic effect is responsible may be settled when higher statistics data and significant Dalitz plots become available.

Establishing the existence of other members of the $\mathbf{\bar{10}}$ is also important. [42] have noted that the relative photoproduction strengths of Θ and the related Σ_5^+ may be predicted even though the scale of each individually is highly model dependent. The implication is that the production rates should be similar, in particular that for a pentaquark Σ_5 one expects $\sigma(\gamma p \to \Sigma_5^+ K^0) \sim 0.2 - 0.5\sigma(\gamma p \to \Theta^+ \bar{K}^0)$. As either of these can decay into $K_s p$, the absence of any Σ_5^+ signal (even after mixing with known Σ^*) accompanying the claimed Θ in the HERMES data for example raises questions. Thus $\gamma p \to p K_S^0 K_S^0$ should be a source of information about such states.

However, there are enough miracles required to explain the various weird aspects of this state, and there are apparent inconsistencies, such as the absence of other states, differing conclusions on the width (is it $\sim 10 - 20$MeV or ~ 1MeV?) that one has to keep clearly in mind the possibility that it simply does not exist. Time, and most important, statistics will tell.

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