History of Exotic Meson (4-quark) and Baryon (5-quark) States

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Abstract

I briefly review the history of exotic meson (4-quark) and baryon (5-quark) states, which is rooted in the formalism of Regge pole and duality. There are robust model-independent predictions for the exchange of 4-quark (Baryonium) Regge trajectories in several processes, which are strongly supported by experiment. On the other hand the predictions for the spectroscopy of 4-quark resonances are based on specific QCD inspired models, with some experimental support. The corresponding predictions for the recently discovered exotic baryon (Pentaquark) state are briefly discussed.
Introduction:

Recently several experiments have reported an exotic baryon resonance $\Theta^+ (1540)$ in the $K^+ n$ channel. It has a narrow width consistent with the experimental resolution ($\Gamma < 20$ MeV), and a tentative spin of $\frac{1}{2}$. Its exotic quantum number, $Y = B + S = 2$, implies that it must belong to the $\overline{10}$ or higher representation of the flavour $SU(3)$. Its minimal quark content is (udud$\bar{s}$). Indeed it represents the first credible signal of an exotic baryon (Pentaquark) state. At the same time the BABAR, CLEO and the BELLE collaborations have found a narrow charmed meson in the $D^+_s \pi^0$ channel at 2317 MeV. Again the width of this resonance is less than the experimental resolution ($\Gamma \leq 10$ MeV), while the tentative spin-parity assignment is $0^+$. Although it has the quantum numbers of a $c\bar{s}$ pair, the low mass, small width and the decay modes of this resonance are very different from the potential model predictions for a $0^+ c\bar{s}$ state. Therefore it has been suggested as a possible 4-quark ($c q\bar{s}q$) state. Moreover BES collaboration have also reported a narrow peak near the $\bar{p}p$ threshold as a possible 4-quark state. These experimental discoveries have revived a great deal of interest in the long sought for exotic meson ($qq\bar{q}\bar{q}$) and baryon ($qqqq\bar{q}$) states.

I shall outline here the history of the exotic meson and baryon physics, discuss its main phenomenological achievements and limitations, and finally look at its implications for the above mentioned exotic baryon (Pentaquark) state.

Many of the present players in this field may not know that the history of exotic meson and baryon states predates QCD. It is based in the $S$-Matrix approach to strong interaction, i.e. the formalism of Regge pole and duality. The Regge poles provide an effective description of composite particles like mesons and baryons, where the spin $J$ is strongly correlated with the particle mass $M$. The main meson and baryon states are seen to lie on linear trajectories in a $J - M^2$ plot with a roughly universal slope, $\alpha'_{m,b} \simeq 1 \text{ GeV}^{-2}$, and intercepts $\alpha_m(0) \simeq 0.5$, $\alpha_b(0) \simeq 0$. Thus the meson and baryon exchanges in the cross-channels are described by virtual particle exchange amplitudes with effective spins of $\alpha_m(t)$ and $\alpha_b(u)$. The resulting energy dependence of forward and backward meson-baryon scattering amplitudes at high energy, $s^{\alpha_m(t\sim 0)}$ and $s^{\alpha_b(u\sim 0)}$, describe the high-energy soft scattering processes remarkably well. Moreover when extrapolated to lower energies, they provide a good average description of the $s$-channel resonance contributions, which shows a duality between the Regge pole and resonance contributions. Thus
the Regge pole and duality formalism provides a consistent and economical
parametrisation of a host of soft two-body scattering processes [4]. Subse-
sequently this has been extended to inclusive scattering cross-section,

\[ a + b \rightarrow c + X, \]

which is related via optical theorem to a 3-body forward elastic scattering
amplitude \( A_{abc} \). The Regge pole and duality formalism for this amplitude
provides an effective description of inclusive scattering as well as resonance
production in the channel \( X \) [4, 5].

**Prediction of Exotic Meson \((qq\bar{q}\bar{q})\) and Baryon \((qqqq\bar{q})\) States:**

It was shown in [7, 8] that the meson-meson and meson-baryon scattering
processes can be consistently described in the framework of Regge pole and
duality using only meson states in the 1,8 and baryon states in the 1,8,10
representations of the flavour \( SU(3) \); but a consistent description of baryon-
antibaryon scattering requires the presence of exotic meson states in the
representations 10, \( \overline{10} \) and 27. Consistency with the meson-meson scattering
result would then require the exotic mesons to have suppressed coupling to
the meson-meson channels, while they couple strongly to baryon-antibaryon.

It was further shown in [8] that a consistent description of the scattering of
these exotic mesons with the normal baryons implies the presence of exotic
baryon states in the \( 10, 27 \) or higher representations. Again consistency with
the earlier result requires these exotic baryons to have suppressed coupling
to the normal meson-baryon channels, while they couple strongly to baryon
and exotic meson channels.

Fig. 1 shows a simple visual representation of these results in terms of the
quark duality diagrams [9]. The first two diagrams show duality between
the normal meson \((q\bar{q})\) and baryon \((qqq)\) states in meson-meson and meson-
baryon scattering. The third diagram shows that in baryon-antibaryon scat-
tering the normal meson \((q\bar{q})\) Regge pole exchanges are dual to exotic meson
\((qq\bar{q}\bar{q})\) resonances and vice versa. The last diagram shows duality between
normal meson \((q\bar{q})\) and exotic baryon \((qqqq\bar{q})\) states in the scattering of exotic
meson with normal baryon. Fig. 2 shows the coupling of the exotic meson
\((qq\bar{q}\bar{q})\) to (a) baryon-antibaryon and (b,c) meson-meson channels. It is clear
from this figure that its couplings to the meson-meson channels can be sup-
pressed by requiring that (i) each pair of particles in the vertex is connected
by at least one quark line, and (ii) a quark-antiquark pair belonging to the same particle can not annihilate one another \cite{10}. This is a generalisation of the famous OZI rule \cite{11}, in which case the forbidden coupling of \(\phi(s\bar{s})\) to \(\rho(ud)\pi(d\bar{u})\) had both these features, so that enacting either one of them was enough. In view of the preferential coupling of the \((qqq\bar{q})\) mesons to the baryon-antibaryon pair they were later christened as Baryoniums in analogy with the heavy quarkonium states \cite{12}. One can easily check that the same rule would ensure preferential coupling of exotic baryon \((qqqq\bar{q})\) states to Baryonium-baryon channels while suppressing it to normal meson-baryon channels. It is customary to call these exotic baryons simply Pentaquark states.

**Evidences of Baryonium \((qqq\bar{q})\) Trajectory Exchange:**

It is not widely known that duality and Regge phenomenology of Baryonium states has had a number of spectacular successes. There are several strong experimental evidences suggesting the exchange of low lying meson Regge trajectories, which contribute very significantly to baryon-antibaryon scattering processes but not in meson-baryon or meson-meson scattering. They occur in two-body as well as inclusive scattering processes and in both exotic and nonexotic channels. These evidences came during the mid and late seventies, when the Regge phenomenology had already gone out of fashion. Therefore it will be worthwhile to briefly summarise them here.

1) The first evidence came from the backward production of normal \((q\bar{q})\) meson resonances in the inclusive process \cite{13}

\[
\pi^- p \rightarrow \Delta^- p X_R(\pi^-, \rho^-, a_1^-, a_2^-, \rho^-),
\]

which proceeds via the exchange of \(\Delta\) Regge trajectory. Thus it corresponds via optical theorem to the elastic scattering amplitude \(A_{\pi^-\bar{p}} \sim A_{\rho^-\bar{\Delta}}\), i.e. a baryon-antibaryon amplitude. As one sees from Fig. 3, the normal \((q\bar{q})\) resonance contributions to this channel are dual to Baryonium \((qqq\bar{q})\) trajectory exchange (3a) and vice versa (3b). The Baryonium trajectory was estimated from the duality prediction

\[
\sigma_{\pi^- p \rightarrow p X_R(M_R)} \sim A_{\rho^-\bar{\Delta}}(M_R) \propto (M_R^2)^{\alpha_B(0)},
\]

which indeed gave a low intercept \((\alpha_B(0) \sim -0.5)\). Moreover these resonances were found to be dual to a normal meson trajectory \((\alpha_m(0) \sim -0.5)\).
5) in the forward production process, which corresponds to a meson-
meson channel [14].

2) The difference of inclusive cross-sections,

$$\Delta_{pp}(\pi^-) = \sigma_{\bar{p}p\to\pi^-X} - \sigma_{pp\to\pi^-X} \sim A_{\bar{p}}\Delta' - A_p\Delta', \quad (4)$$

represents the difference between the corresponding antibaryon-baryon
and baryon-baryon scattering amplitudes. Regge analysis of the energy
dependence of $\Delta_{pp}(\pi^-)$ showed the presence of a large contribution from
a low lying trajectory ($\alpha_B(0) \simeq -1$) in addition to the normal meson
trajectory ($\alpha_m \simeq 0.5$) [15]. In contrast the cross-section differences,
$\Delta_{Kp}(\pi^-)$ and $\Delta_{\pi p}(\pi^-)$, were well described by the normal meson tra-
jectory over the same energy range.

3) The energy dependence of the $\bar{p}p$ and $pp$ total cross-section difference
$(\Delta_{pp})$ shows a similar evidence for a low lying Baryonium trajectory
($\alpha_B(0) \sim -0.5$), in addition to the normal meson trajectory ($\alpha_m(0) \sim
+0.5$), while $\Delta_{Kp}$ is well fitted by the $\alpha_m(0)$ alone [16]. Although the
size of the $\alpha_B(0)$ contribution for $\Delta_{pp}$ is smaller than the inclusive case
the precision of the total cross-section data is much better, so that the
signal is quite unmistakable.

4) Finally the forward cross-sections for the inelastic baryon-baryon scat-
tering processes with exotic $t$-channel like $pn \to \Delta^-\Delta^{++}$, $\bar{p}p \to \bar{Y}^{++}Y^{*-}$
and $\bar{p}p \to \Sigma^+\Sigma^-$ are at least an order of magnitude higher than the
corresponding meson-baryon scattering processes [16,17]. This can be
interpreted as evidence for exotic Baryonium exchange contribution.
In particular a fit to the $pn \to \Delta^-\Delta^{++}$ cross-section in terms of a
non-strange exotic baryonium exchange again gives a low intercept of
$\alpha_B(0) \sim -0.5$. Moreover the coupling is roughly of similar size as the
Baryonium coupling to $\Delta_{pp}$ [16].

Thus the phenomenological evidences for Baryonium trajectory ex-
change contributions are too strong to be fortuitous. On the other hand
the phenomenological support for Baryonium resonance spectroscopy
is relatively modest, as we see below.
Status of Baryonium \((qq\bar{q})\) Resonances:

Several resonances, both narrow and broad, have been reported to decay mainly into the \(\bar{p}p\) channel \(18\). But they are not enough to reproduce the normal \((qq)\) Regge trajectory exchange contribution to this channel as per the duality diagram of Fig. 1c \(19\). So one would require many of the resonances below the \(\bar{p}p\) threshold to be \(qq\bar{q}\) states. In fact there is a large excess of meson resonances in this region compared to the potential model prediction for the \(q\bar{q}\) states; and many of them can be \(qq\bar{q}\) states \(20\). They have normal widths, which may appear to conflict with the above mentioned OZI rule. But since they all have nonexotic quantum numbers, they could have large mixing with the \(q\bar{q}\) states. This would account for their normal decay widths into the meson-meson channels like those of the glueball candidates. But in any case it is outside the scope of the duality and Regge formalism to predict the spectroscopy of Baryonium resonances. For this purpose several QCD inspired models have been suggested – e.g. the diquark models of \(21\) and \(22\), and the colour junction model of \(23\).

Let us briefly discuss the models of \(21\) and \(22\), since they are comparatively simple and closely related to one another. They envisage the \(qq\bar{q}\bar{q}\) state to be composed of a highly correlated diquark and antidiquark pair. The diquarks in the antisymmetric colour state \(\mathbf{3}\) experience a strongly attractive colour force. Consequently there are diquark and antidiquark \(S\) wave bound states with the following colour \(SU(3)\), flavour \(SU(3)\) and spin \(SU(2)\) representations, which ensure their overall antisymmetry – i.e.

\[
qq \rightarrow (\mathbf{3}_c, \mathbf{3}_f, 1), (\mathbf{3}_c, \mathbf{6}_f, 3); \quad \bar{q}\bar{q} \rightarrow (\mathbf{3}_c, \mathbf{3}_f, 1), (\mathbf{3}_c, \mathbf{6}_f, 3).
\]  

(5)

The resulting colour singlet \(qq\bar{q}\bar{q}\) states have the flavour \(SU(3)\) representations and spin,

\[
9_f, J = L; \quad 18_f, J = L \pm 1; \quad 36_f, J = L \pm 2;
\]

where \(L\) is the orbital angular momentum between the diquark and the antidiquark states.

The difference between the two models is that, unlike Chan and Hogaasen \(22\), Jaffe \(21\) rejects OZI suppression of the decay diagram of Fig. 2b. Instead he treats it as a OZI superallowed decay, which should have a larger width than the usual OZI allowed decay of Fig. 2a. Consequently he predicts the \(qq\bar{q}\bar{q}\) states to be even broader resonances than the \(q\bar{q}\) mesons and decay
mainly into the meson-meson channels. But as explained in [18, 22] and the last paper of ref. [21], it will be more reasonable to associate the two types of decay with different states of the orbital angular momentum $L$. For $L = 0$ the diquark and antidiquark states would have overlapping wavefunctions. This would facilitate interaction between their constituent quark and antiquark, leading to their dissociation into two $q\bar{q}$ pairs (Fig. 2b). But for $L \geq 1$ the spatial separation between the diquark and antidiquark would inhibit interaction between their constituents. In this case it will be easier for the colour $\overline{3}$ diquark to combine with a colour 3 quark from the vacuum to form a baryon (Fig. 2a). Thus one would expect the light ($L = 0$) $qq\bar{q}\bar{q}$ states to have uninhibited decay into meson-meson channels, while the heavier ones ($L \geq 1$) decay mainly into baryon-antibaryon channels.

Both the models predict the lightest flavour nonet ($9_f$) states of eq. (6) to occur below 1 GeV, while the lightest exotic states ($18_f$ and $36_f$) occur in the mass range of 1–2 GeV. Indeed the lightest $0^+$ states of the Particle Data Group [20] have been interpreted by Jaffe [21] as members of the lightest flavour nonet state of $qq\bar{q}\bar{q}$ (see also [24]). However, there is no distinctive prediction of these models which can be used as a smoking gun signal for the $qq\bar{q}\bar{q}$ resonance. In fact all the $qq\bar{q}\bar{q}$ resonance candidates of [20] are also amenable to alternative interpretations. This is also true for the narrow charmed meson resonance, discovered recently [2]. It goes without saying that an unmistakable signal for a $qq\bar{q}\bar{q}$ meson will be a resonance seen in an exotic channel. But there is no credible evidence for such a signal even after 35 years of their prediction.

**Status of the Exotic Baryon (Pentaquark) Resonance:**

This brings us finally to the exotic baryon (Pentaquark) state we had started with. As mentioned above the $\Theta^+$ (1540) resonance has an exotic quantum number, $Y = 2$, which means it belongs to $\overline{10}$ or higher representation of flavour $SU(3)$ and has a minimal quark content of $udud\bar{s}$. Indeed this is the first credible signal of an exotic hadron resonance, although it still needs further confirmation. Arguments for and against the resonance interpretation of this peak are given e.g. in [25] and [26] respectively. Meanwhile the NA49 collaboration [27] has presented evidence for a similar narrow peak in another exotic baryon channel with $S = -2$ and $I = 3/2$, which could be a member of the same $SU(3)$ multiplet as the $\Theta^+(1540)$. It should be mentioned here that the mass and the narrow width of $\Theta^+(1540)$ were predicted
remarkably well by the Skyrme model along with a spin-parity of $\frac{1}{2}^+ [28]$. It has been emphasised by many authors however that this agreement could be fortuitous (see e.g. [29, 30]). Firstly this model approximates QCD only in the $N_c \to \infty$ limit. For $N_c = 3$, even the two-flavour (chiral $SU(2) \times SU(2)$) model predicts spurious exotic baryons with $(I, J) = (\frac{5}{2}, \frac{5}{2}), (\frac{7}{2}, \frac{7}{2}), \cdots$, which have to be discarded as artifacts. Moreover for $KN$ scattering it relies heavily on chiral $SU(3) \times SU(3)$ symmetry, which is badly broken in nature. Therefore there are enough reasons for reserve.

Early quark models based on 5 uncorrelated quarks predicted a host of light Pentaquark states with negative parity below 1.5 GeV [31], while none have been found in the data. Subsequent studies have found evidence for strong diquark correlation even for the normal ($qqq$) baryon spectrum [32]. For instance the quark-diquark ($3c - 3\bar{c}$) model for baryons implies similar colour dynamics as the ($q\bar{q}$) mesons, which helps to explain the equal slopes of the corresponding Regge trajectories. Therefore the interpretations of the Pentaquark signal are mainly based on strongly correlated diquarks [30, 33-35]. In particular Jaffe and Wilczek [30] have interpreted $\Theta(ududs)$ in terms of a simple extension of the diquark model of [21]. They assume each $ud$ pair to be the lightest diquark of eq. [5], i.e. a $S$ wave bound state, antisymmetric in colour, flavour and spin ($\bar{3}_c, \bar{3}_f, 1$). The two $ud$ pairs must combine into a colour antisymmetric $3_c$ in order to form a colour singlet baryon with the $\bar{s}(3_c)$. Therefore these two diquark $(ud)$ states must be spatially antisymmetric, which suggests $L = 1$. The $S$ wave bound state of $\bar{s}$ with this $(L = 1)$ pair of scalar diquarks will then have $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$. The lighter state ($\frac{1}{2}^+$) is identified with the $\Theta (1540)$. Evidently the two $ud$ pairs form a flavour symmetric state $8_f$, which combines with the $\bar{s}(3_f)$ to form a $18_f = 10_f + 8_f$. They predict the mass splittings between the various baryon Isospin multiplets belonging to this 18-plet representation, and compare it with the corresponding spectrum of the chiral soliton (Skyrme) model [28]. It is fair to say however that this model has no natural explanation for the very narrow width of $\Theta (1540)$. Moreover the results of [30] have been strongly criticised in [36] using the effective Hamiltonian approach to QCD, which gives much larger mass and width for $\Theta$ in this model. Similarly, Shuryak and Zahed [33] have also estimated a larger $\Theta$ mass of $\sim 1880$ MeV in this model due to the orbital excitation ($L = 1$) between the diquark pair. So they have suggested an alternative model, where the two diquarks are in a relative $L = 0$ state, but one of them is a tensor ($P$ wave) diquark. On the
other hand an $I = 2$ assignment for $\Theta$ has been suggested in [33] to account for its narrow decay width into the $KN$ channel via Isospin violation. Other alternatives have been suggested e.g. in ref. [35]. Thus in short, the jury is still out on the correct theoretical model for the $\Theta$ (1540) resonance.

Let me conclude by pointing out two model independent predictions for this exotic baryon from the duality and Regge formalism. (i) The exotic baryon ($qqqq\bar{q}$) was predicted to have suppressed coupling to the normal meson-baryon channel like $KN$, while having normal coupling to the exotic meson ($qq\bar{q}q$) - baryon ($qqq$) channel [8]. This feature can be justified in the Jaffe-Wilczek model [30] by a similar reasoning as that used above to justify inhibited coupling of $L \geq 1$ Baryoniums to meson-meson channels. The spatial separation between the two $(ud)$ diquarks in relative $L = 1$ state inhibits exchange of their constituents. This suppresses the $\Theta(udud\bar{s}) \rightarrow K(d\bar{s})N(udu)$ decay, which in analogous to Fig. 2b. But it allows $\Theta(udud\bar{s}) \rightarrow \kappa(ud\bar{s}u)N(udu)$, where one of the $(ud)$ diquarks in $\Theta$ absorbs a $u$-quark from the vacuum to form a colour singlet $N$, while the associated $\bar{u}$ is absorbed by $\bar{s}$ to form a 4-quark meson (Baryonium) $\kappa$ (Fig. 1d). Now the lightest 4-quark strange meson $\kappa$ is predicted to be a scalar of 800–900 MeV mass in [21, 30], while there is no clear experimental candidate for such a state below 1 GeV. So in either case the $\Theta$ (1540) lies below the $\kappa N$ threshold and hence would be expected to have only a narrow decay width into the $KN$ channel. A similar conclusion is reached in a recent study of $\Theta$ as a bound state of $N$ and a scalar $\kappa$ of 800–900 MeV mass in the chiral perturbation theory [37]. (ii) Because of its uninhibited coupling to the $\kappa$ ($qq\bar{q}q$) – $N (qqq)$ channel one expects significant $\Theta$ production cross-section in

$$pn \rightarrow \kappa \land \Theta,$$ (7)

via the exchange of a $\kappa$ Baryonium ($qq\bar{q}q$) Regge trajectory (Fig. 4). As discussed above there are several experimental evidences for a low lying Baryonium trajectory exchange. Hence one expects a significant cross-section for the above process only at relatively low incident energy of $\lesssim 4$ GeV, say. Therefore this production process can be looked for at any low energy high intensity proton accelerator. I hope the concerned experimental groups will undertake this investigation.

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References

[1] LEPS Collaboration: T. Nakano et al., Phys. Rev. Lett. 91 (2003) 012002; CLAS Collaboration: S. Stepanyan et al., hep-ex/0307018; V. Kubarovsky et al., hep-ex/0307088; SAPHIR Collaboration: J. Barth et al., hep-ex/0307083; DIANA Collaboration: V.V. Barmin et al., hep-ex/0304040.

[2] BABAR Collaboration: B. Aubert et al., Phys. Rev. Lett. 90 (2003) 242001; CLEO Collaboration: D. Besson et al., hep-ex/0305017; BELLE Collaboration: K. Abe et al., hep-ex/0307041. The BELLE collaboration has also reported a narrow charmonium state at 3872 MeV (hep-ex/0309032), whose mass and radiative decay width differ from the potential model predictions for a \( c\bar{c} \) state.

[3] BES collaboration: J.Z. Bai et al., Phys. Rev. Lett. 91 (2003) 022001; see also BELLE collaboration: K. Abe et al., Phys. Rev. Lett. 88 (2002) 181803 and 89 (2002) 151802.

[4] R.J.N. Phillips and D.P. Roy, Rep. on Prog. in Phys. 37 (1974) 1035.

[5] A.H. Mueller, Phys. Rev. D2 (1970) 2963.

[6] S.N. Ganguli and D.P. Roy, Phys. Rep. 67 (1980) 201.

[7] J.L. Rosner, Phys. Rev. Lett. 21 (1968) 950.

[8] D.P. Roy and M. Suzuki, Phys. Lett. B28 (1969) 558.

[9] J.L. Rosner, Phys. Rev. Lett. 22 (1969) 689.

[10] P.G.O. Freund, R. Waltz and J.L. Rosner, Nucl. Phys. B13 (1969) 237.

[11] S. Okubo, Phys. Lett. 5 (1963) 165; C. Zweig, CERN Report No. TH-401 (1964); J. Izuka et al., Prog. Theor. Phys. 35 (1965) 1061.

[12] G.F. Chew, Proc. Antiproton-proton Conf., Stockholm (1976).

[13] P. Hoyer, R.G. Roberts and D.P. Roy, Phys. Lett. B44 (1973) 258.

[14] P. Hoyer, R.G. Roberts and D.P. Roy, Nucl. Phys. B56 (1973) 173.
[15] R.V. Gavai and D.P. Roy, Phys. Lett. B82 (1979) 139.

[16] R.V. Gavai and D.P. Roy, Nucl. Phys. B137 (1978) 301.

[17] B. Nicolescu, Nucl. Phys. B134 (1978) 495.

[18] For a review see L. Montanet, G.C. Rossi and G. Veneziano, Phys. Rep. 63 (1980) 149; see also J-M. Richard, Nucl. Phys. Proc. Suppl. 86 (2000) 361.

[19] M.R. Pennington, Nucl. Phys. B137 (1978) 77; R.V. Gavai and D.P. Roy, Phys. Lett. B88 (1979) 359.

[20] Review of Particle Properties : K. Hagiwara et al., Phys. Rev. D66 (2002) 01001 (see the review on Non-$q\bar{q}$ candidates by C. Amsler on page 754).

[21] R.J. Jaffe, Phys. Rev. D15 (1977) 267 and 281; Phys. Rev. D17 (1978) 1444.

[22] Chan Hong-Mo and H. Hogaasen, Phys. Lett. B72 (1977) 121; Nucl. Phys. B136 (1978) 401. For extension to flavour $SU(4)$ see e.g. R. Anderson and G.C. Joshi, Phys. Rev. D20 (1979) 736.

[23] G.C. Rossi and G. Veneziano, Nucl. Phys. B123 (1977) 507.

[24] F.E. Close and N.A. Tornqvist, hep-ph/0204205.

[25] N. Kelkar, M. Nowakowski and K. Khemchandani, J. Phys. G29 (2003) 1001.

[26] A.R. Dzierba et al., hep-ph/0311125.

[27] NA49 collaboration: C. Alt et al., hep-ex/0310014.

[28] A. Manohar, Nucl. Phys. B248 (1984) 19; M. Chemtob, Nucl. Phys. B256 (1985) 600; M. Praszalowicz, in Skyrmions and Anomalies, World Scientific (1987); D. Diakonov, V. Petrov and M.V. Polyakov, Z. Phys. A359 (1997) 305.

[29] N. Itzhaki, I.R. Klebanov, P. Ouyang and L. Rostelli, hep-ph/0309305.

[30] R. Jaffe and F. Wilczek, hep-ph/0307341.
[31] D. Strottman, Phys. Rev. D20 (1979) 748; H. Hogasen and P. Sorba, Nucl. Phys. B145 (1978) 119.

[32] A. Martin, Z. Phys. C32 (1986) 359; T. Schafer, E. Shuryak and J. Verbaarschot, Nucl. Phys. B412 (1994) 143; M. Anslmino, E. Predazzi, S. Ekelin, S. Fredriksson and D.B. Lichtenberg, Rev. Mod. Phys. 65 (1993) 1199.

[33] E. Shuryak and I. Zahed, hep-ph/0310270

[34] S. Capstick, P.R. Page and W. Roberts, Phys. Lett. B570 (2003) 185; P.R. Page, hep-ph/0310200

[35] S. Nussinov, hep-ph/0307357; S. Zhu, hep-ph/0307345; M. Karliner and H.J. Lipkin, hep-ph/0307243; C. Carlson et al., hep-ph/0307396; F. Csikor et al., hep-lat/0309090; S. Sasaki, hep-lat/0310014

[36] I.M. Narodetskii, Y.A. Simonov, M.A. Trusov and A.I. Veselov, hep-ph/0310118

[37] F.J. Llanes-Istrada, E. Oset and V. Mateu, nucl-th/0311020
Figure 1: The quark duality diagrams for (a) meson-meson, (b) meson-baryon, (c) baryon-antibaryon and (d) baryon-Baryonium scattering. The last one is the formation channel for Pentaquarks.

Figure 2: The coupling of Baryonium into (a) baryon-antibaryon and (b,c) meson-meson channels. Only the 1st one is OZI allowed.
Figure 3: The quark duality diagrams for backward production of (a) normal meson and (b) Baryonium resonances.

Figure 4: The quark diagram for Θ production via Baryonium exchange.