HADRON SPECTROSCOPY WITHOUT CONSTITUENT GLUE

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Abstract
Glueballs and hybrids are predicted to exist but searches for them have failed to provide conclusive evidence. One–gluon exchange is not an important part of strong interactions in this energy regime. Instead, quarks seem to interact indirectly, via changes of the QCD vacuum. Strong interactions seem to be governed by instanton–induced interactions; the chiral soliton model gives a more suitable interpretation of the $\Theta^+(1540)$ than models based on the dynamics of four quarks and one antiquark.

1   The scientific scope

There is only little understanding of the dynamics of quarks and gluons in the intermediate energy regime where meson and baryon resonances dominate strong interactions. Chiral symmetry, expected to hold for nearly massless quarks, is spontaneously broken, and quarks acquire an effective 'constituent' mass. In quark models, mesons and baryons are thus described by constituent quarks in a confining potential. The interaction between quarks is more complicated than just a confinement potential suggests: the full interaction is parameterized by some kind of additional 'residual' interaction, by 'effective' one–gluon exchange, by exchange of pseudoscalar mesons (i.e. Goldstone bosons), or by instanton induced interactions. From deep inelastic scattering it is known that baryons are more complex. The structure functions reveal a rich dynamical sea of quark–antiquark pairs, but there is no bridge from the high–energy partonic structure to the dynamics of constituent quarks and their interaction. In recent years, two interpretations have been developed of strong interactions physics in the confinement region. One interpretation underlines the importance of the gluon fields. The residual interaction between quarks is given by an effective one–gluon exchange, gluons can - like quarks - develop an effective mass. Gluons manifest themselves in new degrees of freedom in spectroscopy, in glueballs and in hybrids. The proponents of this picture interpret the $\Theta^+(1540)$ as pentaquark, as bound state of four quarks and one (strange) antiquark. The second view is proposed in the chiral soliton picture. Quarks interact dominantly by changing the vacuum, like Cooper pairs interact via phonon exchange. In this picture, the $\Theta^+(1540)$ arises naturally as member of an anti-decuplet. Quarks interact via instanton–induced interactions. The forces are transmitted by vacuum fluctuations of the gluon fields, not as direct quark–quark interactions. Glueballs and hybrids are no obvious features in this kind of theory. A recent experimental survey can be found in [1].

2   Gluon exchange or instanton–induced interactions in baryons ?

The three–quark valence structure of baryons supports a rich spectrum which is very well suited to study the effective interactions between quarks in resonances. Fig. 1 shows a Regge trajectory of Δ^* and of N* resonances having intrinsic spin 3/2.
 Nucleon resonances with intrinsic spin 1/2 are discussed next. These can be separated into groups of states with even parity coming from a symmetric 56-plet; odd–parity baryons may come from a 70-plet with mixed symmetry, from the totally antisymmetric singlet system, or from a decuplet, see Fig. 2. The common feature of each group is the fraction in the wave function which is antisymmetric in spin and in flavor. This fraction is largest for singlet baryons,
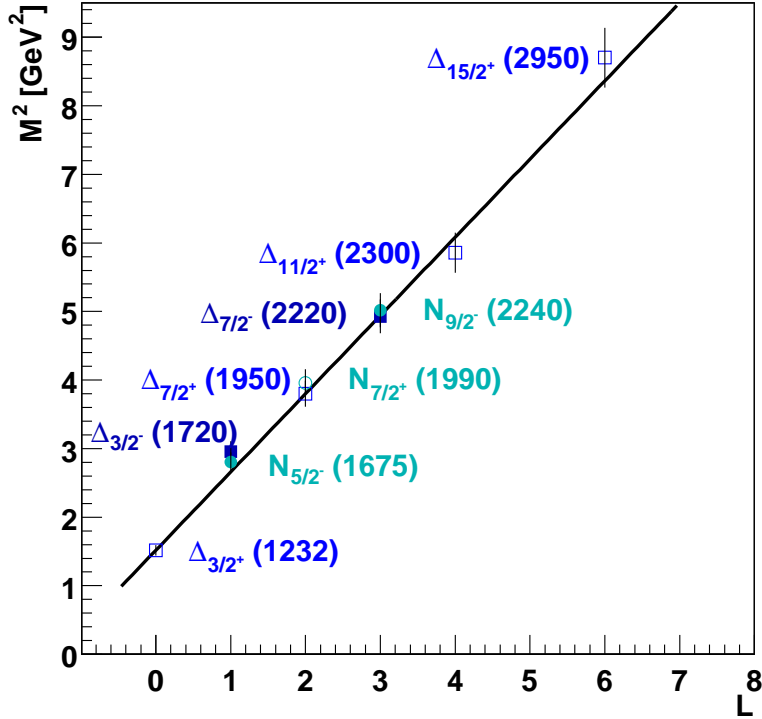
Figure 1. The lowest–mass Δ^* resonances lie on Regge trajectories. If plotted against the intrinsic orbital angular momentum, also negative–parity resonances fall onto the trajectory. For even parity the mass for $J = L+3/2$ is plotted, for odd parity that for $J = L + 1/2$. States with given L but different J are mass approximately degenerate. This is the well known spin–orbit puzzle: from one–gluon exchange, large spin–orbit splittings are expected. Surprising, perhaps, is the observation that nucleon resonances with intrinsic spin $S = 3/2$ are degenerate in mass with the Δ series.

reduced for octet baryons from a 56-plet, even smaller for octet baryons from a 70-plet, and vanishes for decuplet baryons. For each group, there seems to be a common shift in mass square. This shift is proportional to the fraction of the baryon wave function which is antisymmetric in spin and in flavour. This is a very characteristic pattern which must reflect the symmetry properties of the underlying interaction. Indeed, instanton–induced interactions follow this symmetry. Thus the pattern observed in Fig. 2 provides strong support for instanton–induced interactions being the residual interaction which complements the confinement forces. The pattern can be formulated as simple baryon mass formula having four parameters only. It reproduces very well the observed baryon mass spectrum, with a χ^2 which is much better than for a model based on one–gluon exchange interactions (which suppresses spin–orbit effects by arbitrarily assuming that spin–orbit forces and the Thomas precession in the confinement field compensate each other).
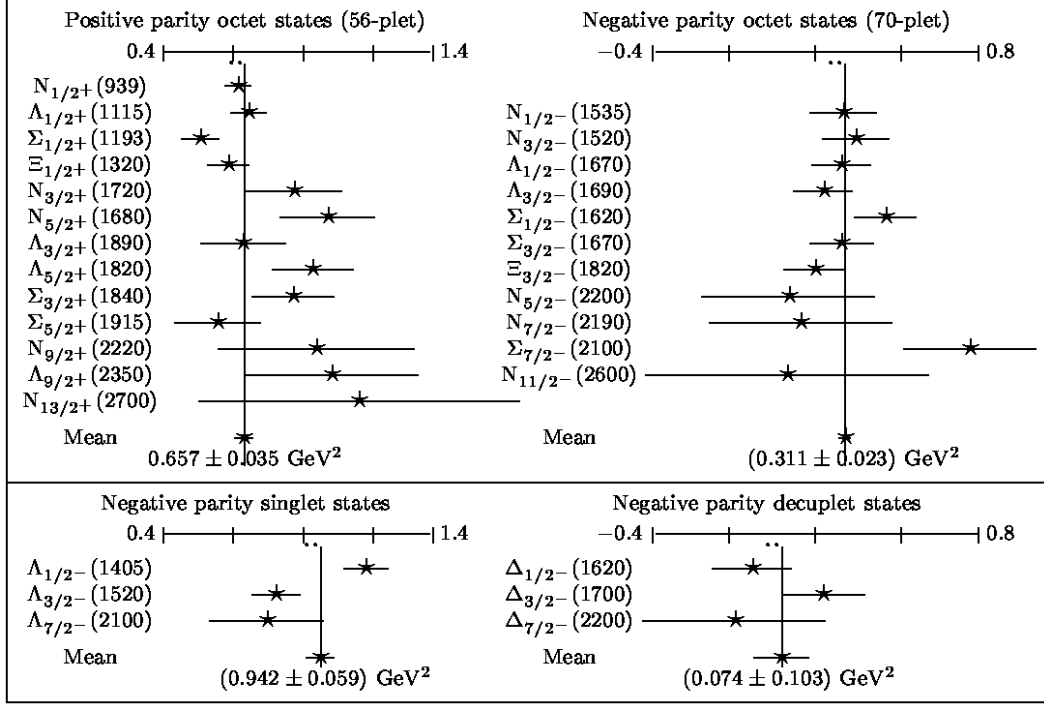
Positive parity octet states (56-plet)

0.4 ⊢————————⊣ 1.4

$N_{1/2+}(939)$
$\Lambda_{1/2+}(1115)$
$\Sigma_{1/2+}(1193)$
$\Xi_{1/2+}(1320)$
$N_{3/2+}(1720)$
$N_{5/2+}(1680)$
$\Lambda_{3/2+}(1890)$
$\Lambda_{5/2+}(1820)$
$\Sigma_{3/2+}(1840)$
$\Sigma_{5/2+}(1915)$
$N_{9/2+}(2220)$
$\Lambda_{9/2+}(2350)$
$N_{13/2+}(2700)$

Mean 0.657 ± 0.035 GeV^2

Negative parity octet states (70-plet)

−0.4 ⊢————————⊣ 0.8

$N_{1/2-}(1535)$
$N_{3/2-}(1520)$
$\Lambda_{1/2-}(1670)$
$\Lambda_{3/2-}(1690)$
$\Sigma_{1/2-}(1620)$
$\Sigma_{3/2-}(1670)$
$\Xi_{3/2-}(1820)$
$N_{5/2-}(2200)$
$N_{7/2-}(2190)$
$\Sigma_{7/2-}(2100)$
$N_{11/2-}(2600)$

Mean (0.311 ± 0.023) GeV^2

Negative parity singlet states

0.4 ⊢————————⊣ 1.4

$\Lambda_{1/2-}(1405)$
$\Lambda_{3/2-}(1520)$
$\Lambda_{7/2-}(2100)$

Mean (0.942 ± 0.059) GeV^2

Negative parity decuplet states

−0.4 ⊢————————⊣ 0.8

$\Delta_{1/2-}(1620)$
$\Delta_{3/2-}(1700)$
$\Delta_{7/2-}(2200)$

Mean (0.074 ± 0.103) GeV^2

Figure 2. Mass shift (in GeV^2) with respect to the Δ Regge trajectory. The nucleon has a (squared) mass of 0.88 GeV^2, the $\Delta(1232)$ of 1.52 GeV^2. The difference, 0.64 GeV^2, is plotted. For resonances with strangeness, the Regge trajectory starts at the $\Sigma^*(1385)$ mass but has the same slope.

3 Is there convincing evidence for glueballs ?

Glueballs, hybrid mesons and hybrid baryon are predicted by QCD inspired models and may even be a consequence of QCD on the lattice. But inspite of intensive searches, no convincing evidence for their discovery has been reported.

3.1 Search for the pseudoscalar glueball

The Particle Data Group[2] decided in their 2004 edition that there is sufficient evidence that the former $\eta(1440)$ is split into two components, the $\eta(1405)$ component decaying mostly into $a_0(980)\pi$ and $\eta\sigma$, and the $\eta(1474)$ with $K^*\bar{K}$ as preferred decay mode. The following interpretation of the pseudoscalar mesons is offered:

π	η		η'	K
$\pi(1300)$	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$K(1460)$
$n\bar{n}$	$n\bar{n}$	glueball	$s\bar{s}$	$n\bar{s}$

The $\eta(1295)$ and $\pi(1300)$ mesons have the same masses, hence the $\eta(1295)$ and $\eta(1475)$ have likely a nearly ideal mixing angle, with $\eta(1475)$ being the $s\bar{s}$ state. The $\eta(1405)$ does not find a slot in sthe spectrum of $\bar{q}q$ mesons; the

4

low mass part of the $\eta(1440)$ could be a glueball.

Radiative J/ψ decays show an asymmetric peak in the $\eta(1440)$ region. Both $\eta(1405)$ and $\eta(1475)$ contribute to the process. Radial exciations are hence produced in radiative J/ψ decays (not only glueballs). But then, $\eta(1295)$ should also be produced, but it is not! There is also no evidence for $\eta(1295)$ from $\gamma\gamma$ fusion at LEP, nor from a study of $\gamma\gamma \to K_s^0 K^\pm \pi^\mp$, but $\eta(1440)$ is seen[3]. The $\eta(1440)$ coupling to photons is much stronger than that of $\eta(1295)$: the assumption that the $\eta(1295)$ is a $(u\bar{u} + d\bar{d})$ radial excitation must be wrong! The mass of the pseudoscalar resonance in $\gamma\gamma$ fusion is about 1460 MeV, and it decays mainly into K*K. Hence the state is identified with the $\eta(1475)$.

The Crystal Barrel collaboration searched for the $\eta(1295)$ and $\eta(1440)$ in the reaction $p\bar{p} \to \pi^+ \pi^- \eta(m)$, $\eta(m) \to \eta\pi^+\pi^-$[4] where m is a running mass. A clear pseudoscalar resonance signal was observed at 1405 MeV. A scan for an additional 0^+0^{-+} resonance provided no evidence for the $\eta(1295)$. A resonance at 1480 MeV was seen, with $M = 1490 \pm 15, \Gamma = 74 \pm 10$. Again, there is no reason why the $\eta(1405)$ and the $\eta(1475)$ were observed but not the $\eta(1295)$. The latter resonance is seen only in the charge exchange reaction $\pi^- p \to n\eta\pi\pi$. In the 1970's, the $a_1(1260)$ properties were obscured by the so–called Deck effect (ρ–π re-scattering in the final state). Possibly, $a_0(980)\pi$ re-scattering fakes a resonance–like behavior; otherwise $\eta(1295)$ might be mimicked by feed–through from $f_1(1285)$. In any case, we exclude $\eta(1295)$ from the further discussion.

The $\eta(1440)$ is not produced as $\bar{s}s$ state but decays with a large fraction into $K\bar{K}\pi$ and it is split into two components. These anomalies are likely due to a node in the $\eta(1440)$ wave function. The node has an impact on the decay matrix element which were calculated by[5] within the $^3P_0$ model.
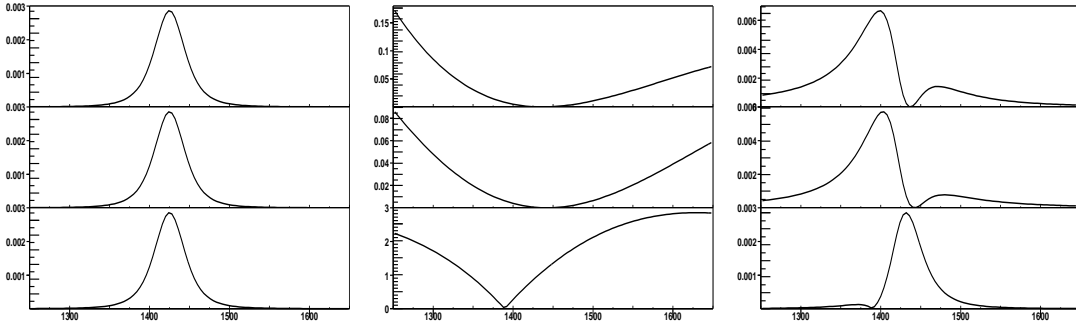

Figure 3. Amplitudes for $\eta(1440)$ decays to $a_0\pi$ (first row), $\sigma\eta$ (second row): K*$\bar{K}$ (third row) the Breit-Wigner functions are shown on the left, then the squared decay amplitudes [5] and, on the right, the resulting squared transition matrix element.

The $\eta(1440) \to a_0(980)\pi$ and $\to$ K*K distributions peak at different masses, about at the $\eta(1405)$ and $\eta(1475)$ masses. Hence there is no need to introduce

the $\eta(1405)$ and $\eta(1475)$ as two independent states. One $\eta(1420)$ and the assumption that it is a radial excitation describes the data. The phase motions of the $a_0(980)\pi$ or $\sigma\eta$ isobar[4] are compatible with only one pseudoscalar resonance being present in the mass range from 1200 to 1500 MeV. Hence the following states are identified as pseudoscalar ground states and radial excitations:

1^1S_0	π	η'	η	K
2^1S_0	$\pi(1300)$	$\eta(1760)$	$\eta(1420)$	K(1460)

3.2 Search for the scalar glueball

The lowest–mass glueball has scalar quantum numbers. Its predicted mass (~ 1700 MeV) falls into a region in which one may hope to get a consistent picture of the mass spectrum of all scalar mesons. Table 1 lists the spectrum of scalar mesons as given by the Particle Data Group.

The $f_0(600)$, the lowest mass scalar meson, is often called $\sigma(600)$. The Particle Data Group assigns to it a mass range from 400 to 1200 MeV. In partial wave analyses, it is seen as a pole at about 500 MeV. However, the phase reaches $90°$ only at ~ 780 MeV. A similar pole is observed in $K\pi$ scattering; it is often called $\kappa(800)$. The nature of σ and κ is hotly debated: they may be $qq\bar{q}\bar{q}$ mesons[6], relativistic S-wave $q\bar{q}$ states ('chiralon')s[7], or they might be due to attractive $\pi\pi$ or $K\pi$ interactions, generated by 'left–hand cuts' in a technical language. Practically, the $\sigma(600)$ and $\kappa(900)$ do not play a role in the discussion of glueballs, and the reader is referred to a recent review[8]. The $a_0(980)$ and $f_0(980)$ are often considered as $K\bar{K}$ molecular–like bound states[9,10,11].

Table 1
The scalar mass spectrum[2].

I = 1/2	I = 1	I = 0	
		$f_0(600)$	$\sigma(600)$ *meson*
K(900)			chiral partner of the π
	$a_0(980)$	$f_0(980)$	$K\bar{K}$ molecules
		$f_0(1370)$	$q\bar{q}$ state
$K_0^*(1430)$	$a_0(1490)$	$f_0(1500)$	2 $q\bar{q}$ states, glueball
		$f_0(1710)$	$q\bar{q}$ state
$K_0^*(1950)$			$q\bar{q}$ state
		$f_0(2100)$	$q\bar{q}$ state
		$f_0(2200, 2330)$	$q\bar{q}$ state

The Crystal Barrel collaboration proposed the existence of two further scalar isoscalar mesons, the $f_0(1370)$ and $f_0(1500)$. Their decays were studied in a series of analyses[12]$^-$[13]. Three striking peaks were observed in the $\eta\eta$ invariant mass spectrum produced in $\bar{p}p$ annihilation in flight into $\pi^0\eta\eta$[14], $1500, 1750$ and $2100\,\mathrm{MeV}$. The data were not decomposed into partial waves in a partial wave analysis, so the peaks could have $\mathrm{J^{PC}} = 0^{++}$, 2^{++}, or higher. If the states had $\mathrm{J^{PC}} = 2^{++}$, their decay into $\eta\eta$ would be suppressed by the angular momentum barrier. The peaks were seen very clearly suggesting 0^{++} quantum numbers. The same pattern of states was seen at BES in radiative J/ψ decays[15] into $2\pi^+2\pi^-$. A partial wave analysis confirmed their scalar nature as had been suggested before in a reanalysis of MARKIII data[16]. The $f_0(1500)$, $f_0(1710)$ and the $f_0(2100)$ have a similar production and decay pattern. Neither $f_0(1370)$ nor 'background' intensity was assigned to the scalar isoscalar partial wave.

The first interpretation[17] of the scalar spectrum, also adopted by the Particle Data Group, identifies the $a_0(980)$ and $f_0(980)$ as non–$q\bar{q}$ states. Then there are 10 states in the mass region of interest while the quark model predicts only 9 $(3\,a_{(}1450)$, $4\,\mathrm{K}_0^*(1430)$, and $2\,f_0$'s). One of the states, $f_0(1370)$, $f_0(1500)$ or $f_0(1710)$, must be the scalar glueball! However, the $f_0(1500)$ couples strongly to $\eta\eta'$; these are two SU(3) orthogonal states and cannot come from a singlet. The $f_0(1500)$ must hence have a strong flavor–octet component, it cannot be a pure glueball. The $f_0(1370)$ and $f_0(1500)$ decay strongly to 2π and into 4π and weakly to $\bar{\mathrm{K}}\mathrm{K}$, they both cannot carry a large $\bar{s}s$ component. The $f_0(1370)$ is, probably, too light to be the scalar glueball. So, none of the three states 'smells' like a glueball. A way out is mixing; the two scalar $\bar{q}q$ states and the scalar glueball have the same quantum numbers, they mix and form the three observed states. Table 1 summarizes this interpretation. Several explicit mixing scenarios have been suggested[17]$^-$[23] and some of them are capable of reproducing the decay pattern.

An important ingredient of the 'narrow–glueball' is the interpretation of the $f_0(980)$ and $a_0(980)$ as alien objects, not related to $q\bar{q}$ spectroscopy. Several experiments were directed to determine the structure of these two mesons, like two-photon production[24], Φ radiative decay into $f_0(980)$[25,26] and into $a_0(980)$[27,28], and Z^0 fragmentation [29]. The conclusions drawn from these results are ambiguous. Presumably, the wave function of the $f_0(980)$ and $a_0(980)$ is not just K$\bar{\mathrm{K}}$ but has a complex mass and momentum dependence. Likely, the outer part of the wave function contains a large K$\bar{\mathrm{K}}$ component, in particular close to the K$\bar{\mathrm{K}}$ threshold. The core however may be dominantly $q\bar{q}$. In meson–meson scattering in relative S–wave, coupled channel effects play a decisive role. The opening of thresholds attracts pole positions and the resonances found experimentally do not agree with masses as calculated in quark models. Under normal circumstances, K–matrix poles, poles of the scattering matrix T and positions of observed peaks agree approximately, and the inter-

Table 2

The K–matrix poles of [34] show a remarkable agreement with the results of the Bonn model [35], version B. There is an additional pole at 1400 ± 200 MeV far off the real axis (i.e. ~ 1000 MeV broad), which is a flavor singlet and could be the glueball.

K-matrix poles			Bonn model, B		
	$a_0(980 \pm 30)$	$f_0(680 \pm 50)$		$a_0(1057)$	$f_0(665)$
$K_0^*(1230 \pm 40)$	$a_0(1630 \pm 40)$	$f_0(1260 \pm 30)$	$K_0^*(1187)$	$a_0(1665)$	$f_0(1262)$
		$f_0(1400 \pm 200)$			
		$f_0(1600)$			$f_0(1554)$
$K_0^*(1885^{+50}_{-100})$			$K_0^*(1788)$		
		$f_0(1810 \pm 50)$			$f_0(1870)$

pretation is unambiguous. In S–waves, the situation is more complicated. The mass of the resonance as quoted by experiments is the T matrix pole. Quark models usually do not take into account the couplings to the final state. Here, the K–matrix poles are compared to quark model results, Table 2. The K–matrix poles come from a series of coupled–channel analyses[30,31,32], mean values and errors are estimates provided by one of the authors[34]. The quark model states are from the Bonn model[35], with the Lorentz structure B of the confinement potential. Excellent agreement is observed. The two lowest scalar nonets are identified, and there is one additional state, the $f_0(1400 \pm 200)$. Its couplings to two pseudoscalar mesons are flavor–blind, it is an isoscalar state. So it can be identified as a scalar glueball. The width is problematic, it exceeds 2 GeV. An excellent review of this approach can be found in[31]. The large scalar isoscalar background amplitude has been suggested as the scalar glueball in[36] and[37].

Can the wide resonance be identified with a glueball? This is neither known and nor tested. The ideal way to identify the nature of such a broad state is a comparison of different J/ψ decay modes:

(1) $J/\psi \to \omega\pi\pi$, $J/\psi \to \omega K\bar{K}$, $J/\psi \to \omega\eta\eta$, $J/\psi \to \omega\eta\eta'$, $J/\psi \to \omega 4\pi$
(2) $J/\psi \to \phi\pi\pi$, $J/\psi \to \phi K\bar{K}$, $J/\psi \to \phi\eta\eta$, $J/\psi \to \phi\eta\eta'$, $J/\psi \to \phi 4\pi$
(3) $J/\psi \to \gamma\pi\pi$, $J/\psi \to \gamma K\bar{K}$, $J/\psi \to \gamma\eta\eta$, $J/\psi \to \gamma\eta\eta'$, $J/\psi \to \gamma 4\pi$

I anticipate that the data can be described by the pole positions given in Table 2. The glueball components of scalar mesons do not couple to processes (1) and (2) but only to (3). Thus the glueball component can be identified. Channels containing $\eta\eta$ and $4\pi^0$ would be the best choice since a pion pair may also be produced from two primary gluons by pion or ρ exchange between the gluons, with colour neutralization by soft–gluon exchange. For $\eta\eta$ and $4\pi^0$

this process cannot occur. But also data recoiling against $\pi\pi$ and $K\bar{K}$ should allow a sensitive search for glueball components.

4   Is there convincing evidence for hybrids?

The status of $J^{PC} = 1^{-+}$ exotic mesons has recently been reviewed[38]. The lowest–mass candidate, $\pi_1(1370)$, decays into $\pi\eta$ and must be a four–quark state due to symmetry arguments. A plethora of further four–quark states is then expected, making unrealistic the attempt to identify one of them as hybrid. The N(1440)[39] and the $\Lambda(1600)$[40] were proposed to be hybrid baryons, but these interpretations are not compelling. The $\Theta^+(1540)$, however, is a strong candidate for the anti-decuplet expected from chiral soliton model.

5   Conclusions

There seems to be much more evidence for instanton–induced interactions in hadron spectroscopy than for one–gluon exchange. There is no compelling evidence for gluons as constituent parts in spectroscopy. Finally, the of the $\Theta^+(1540)$ - discussed intensively at this workshop - seem to be more easily interpreted in the chiral–soliton–model than in models based on a special five–quark dynamic.

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