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Five-quark components in baryons

D. O. Riska[1)]

Helsinki Institute of Physics, POB 64, FIN-00014 University of Helsinki, Finland

Abstract While several experiments based on the Drell-Yan process have revealed the presence of light antiquarks in the proton, the experimental signatures for strange quark components remain consistent with 0. Phenomenological studies of meson photoproduction on nucleons with hadronic models indicate that the underprediction of the NΔ transition strengths by the three quark model may be attributed to the missing "meson cloud" contributions. If qqqq$\bar{\text{q}}$ configurations are included in the baryon wave functions the conclusions that emerge are that (a) a combination of at least three different qqqq$\bar{\text{q}}$ configurations are required for a satisfactory description of the nucleon properties and (b) that the vanishing of the axial form factor of the N(1535) resonance is a natural consequence of the cancellation of the contributions of the qqq and qqqq$\bar{\text{q}}$ configurations.

Key words keyword, quark model, baryons

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1 Introduction

Several experiments have revealed the presence of light antiquarks in the proton, by measuring the $\bar{\text{u}}$ and $\bar{\text{d}}$ distributions by the Drell-Yan process, in which leptonic decay of a virtual gamma formed of a quark in the projectile and an antiquark in the target is measured [1]. Four experiments, SAMPLE, HAPPEX, A4 and G0 have measured the strange vector form factors of the proton, which arises from s$\bar{\text{s}}$ quark components. The conclusion from the present versions of these experiments is, however, that these form factors are very small, if not zero [2–4].

The clearest signal for qqqq$\bar{\text{q}}$ state would be the discovery of an explicit pentaquark, as the putative θ^+. While no corroborating evidence for this state has been found in spite of extensive effort [5], the group that first announced it continues to see a sharp peak at its expected position with improved statistics [6].

2 Baryon resonances

There is on the other hand good indirect evidence of multiquark components in the baryons in the failure of the basic qqq to provide a quantitative description of eg the decay of the $\Delta(1232)$ resonance. Quantitative investigation of the the $\Delta - \text{N}$ decay with a unitary hadronic model reveals that when the "pion cloud" contribution is switched off, the decay width is underpredicted by the same $\sim$30% magnitude as with the qqq quark model [7]. When the quark model is extended to include a $\sim$10% qqqq$\bar{\text{q}}$ configuration (with the qqqq subsystem in a symmetric spin-isospin configuration $[4]_{\text{FS}}\{[31]_{\text{F}}[31]_{\text{S}}\}$ the calculated decay width of the $\Delta(1232)$ increases by factors 2–3 [8]. Here F represents flavor (isospin) and S spin. Here the notation [mn..] denotes m boxes in row 1, n in row 2 and so on in the Young pattern that describes the symmetry of the configuration. (In this notation the completely symmetric flavor-spin configuration in the ground state of the qqq model is $[3]_{\text{FS}}\{[21]_{\text{F}}[21]_{\text{S}}\}$). The explicit wave functions that corresponds to the different symmetry configurations for the qqqq subsystem are formed as linear combinations of the appropriate color, flavor, spin and orbital wave functions with S_4 Clebsch-Gordan coefficients as coefficients [9].

The role of the qqqq$\bar{\text{q}}$ configurations is even larger in the case of the next resonance, the N(1440) $1/2^+$ resonance. The 3-quark models in all forms of covariant kinematics leads to order of magnitude underestimates of the decay width of the N(1440) [10]. In the case of the following resonance, the N(1535) $1/2^-$ resonance, the qqq quark model does in contrast provide

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1) E-mail: riska@pcu.helsinki.fi

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a qualitative description of the decay widths.

Recent QCD lattice calculations, albeit still with pion mass values $\sim$500 MeV, suggest that the structure of the N(1440) is complex, in that in their present version its calculated energy remains way above the empirical energy, while in contrast the calculated energy of the N(1535) falls close to the empirical value [11].

3 The axial charge

Calculation of baryon observables in extended quark models, which include multiquark components are complicated because of the need to consider the non-diagonal matrix elements of transition operators between configurations with different numbers of $q\bar{q}$ pairs. In this sense the axial charge operator is an exception, in that its nondiagonal elements involve small components of the quark spinors, and therefore are suppressed.

The recent lattice calculation of the axial charges of the 2 lowest $1/2^-$ resonances - the N(1535) and the N(1650) - is particularly interesting [12]. The calculated values are $g_\mathrm{A}(1535)\simeq 0$ and $g_\mathrm{A}(1650)\simeq 0.55$. These two values are close to the corresponding values $-1/9$ and $5/9$ in the qqq quark model [13].

If the axial charge of the N(1535) actually vanishes, it implies that the multiquark contributions cancel contribution of the qqq component in the wave function. While the contribution of the multiquark components is usually small, because of their small amplitude in the wave function, the cancellation is possible in this case, because of the untypically small contribution $(-1/9)$ of the qqq component.

The 5 possible symmetry configurations for the qqqq subsystem of the $qqqq\bar{q}$ configurations in the N(1535) are listed in Table 1 [14]. These contribute to the axial charge of schematically as:

$$g_\mathrm{A}(\mathrm{N}(1535)) = -1/9\,P_3 + \sum_{n=1}^{5} A_n\,P_n\ . \qquad (1)$$

Here P_3 is the probability of the qqq component and P_n the probabilities of the 5 $qqqq\bar{q}$ components with the respective weights A_n in Table 1.

Note that the first of the $qqqq\bar{q}$ components, which has to contain an s-quark does not contribute to the axial charge (its main role is to enable the η decay branch of the resonance). The key point is though that the next (and the last) configuration in the table have coefficients A_n, which are positive and of order 1, which means that even with only a moderate amount of those $qqqq\bar{q}$ configurations, they can give rise to axial charge contributions that are large enough to cancel the qqq contribution [14].

Table 1. $qqqq\bar{q}$ configurations in the N(1535).

	flavor-spin symmetry	color-spin symmetry	A_n
1	$[31]_\mathrm{FS}[211]_\mathrm{F}[22]_\mathrm{S}$	$[31]_\mathrm{CS}[211]_\mathrm{C}[22]_\mathrm{S}$	0
2	$[31]_\mathrm{FS}[211]_\mathrm{F}[31]_\mathrm{S}$	$[31]_\mathrm{CS}[211]_\mathrm{C}[31]_\mathrm{S}$	+5/6
3	$[31]_\mathrm{FS}[22]_\mathrm{F}[31]_\mathrm{S}$	$[22]_\mathrm{CS}[211]_\mathrm{C}[31]_\mathrm{S}$	−1/9
4	$[31]_\mathrm{FS}[31]_\mathrm{F}[22]_\mathrm{S}$	$[211]_\mathrm{CS}[211]_\mathrm{C}[22]_\mathrm{S}$	−4/15
5	$[31]_\mathrm{FS}[31]_\mathrm{F}[31]_\mathrm{S}$	$[211]_\mathrm{CS}[211]_\mathrm{C}[31]_\mathrm{S}$	+17/18

This description might be more complicated if there is a subtantial configuration mixing between the N(1535) and the N(1650), but recent indications are that the mixing is small [15, 16].

It has also recently been shown, that the helicity amplitude $A_{1/2}$ for γ decay of the N(1535), cannot be well described without a substantial $qqqq\bar{q}$ component in the resonance [17]. In the case of the N(1440) the situation is less clear, as on the one hand inclusion of an explicit $qqqq\bar{q}$ component readily leads to an increase of the calculated decay width, which is sufficient to reach the empirical value, while on the other hand the recent empirical values for the corresponding helicity amplitude [18] are not well described even with such an extension [19]

4 5 quark components in the nucleon

In the case of the nucleon there are 10 possible configurations of the qqqq system of a $qqqq\bar{q}$ component, if strange quark components are neglected[20]. These are listed in Table 2.

Table 2. $qqqq\bar{q}$ configurations in the nucleon.

	spatial symmetry	flavor-spin symmetry
1	[4]	$[31]_\mathrm{FS}[22]_\mathrm{F}[31]_\mathrm{S}$
2	[4]	$[31]_\mathrm{FS}[31]_\mathrm{F}[22]_\mathrm{S}$
3	[4]	$[31]_\mathrm{FS}[31]_\mathrm{F}[31]_\mathrm{S}$
4	[31]	$[4]_\mathrm{FS}[22]_\mathrm{F}[22]_\mathrm{S}$
5	[31]	$[4]_\mathrm{FS}[31]_\mathrm{F}[31]_\mathrm{S}$
6	[31]	$[31]_\mathrm{FS}[22]_\mathrm{F}[31]_\mathrm{S}$
7	[31]	$[31]_\mathrm{FS}[31]_\mathrm{F}[22]_\mathrm{S}$
8	[31]	$[31]_\mathrm{FS}[31]_\mathrm{F}[31]_\mathrm{S}$
9	[31]	$[22]_\mathrm{FS}[22]_\mathrm{F}[22]_\mathrm{S}$
10	[31]	$[22]_\mathrm{FS}[31]_\mathrm{F}[31]_\mathrm{S}$

Alone none of these $qqqq\bar{q}$ components leads to the remarkable $-3/2$ ratio between the proton and the neutron magnetic moments, which is characteristic of the basic qqq configuration in both its nonrelativistic and relativistic versions [21]. This may be inferred from Table 3, where the nucleon magnetic moments for the 7 simplest $qqqq\bar{q}$ configurations in the nucleons are listed. This may also inferred from the comprehensive attempt in Ref. [22] to combine only the first of these qqqq$\bar{\text{q}}$ configurations with the basic qqq configuration.

The desired $-3/2$ ratio can however be obtained with a linear combination of the qqq and the first 3 configurations in Table 3:

$$\psi = \sqrt{P_3}\,\varphi_{[3][21][21]} + \sqrt{\frac{P_5}{\frac{11}{9}b_1+\frac{5}{3}b_2}} \times \left\{ \sqrt{\frac{2}{9}b_1+\frac{2}{3}b_2}\,\varphi_{[4][22][22]} + \sqrt{b_1}\,\varphi^{J=1}_{[4][31][31]} + \sqrt{b_2}\,\varphi^{J=0}_{[4][31][31]} \right\}. \tag{2}$$

Here P_3 and P_5 are the probabilities for the qqq and (total) qqqq$\bar{\text{q}}$ components and b_1 and b_2 are coefficients. The $\bar{q}$ components in the qqqq$\bar{\text{q}}$ wavefunctions is to be understood. A combination of the form (2) with 68 % qqq and 32 % of these qqqq$\bar{\text{q}}$ can in fact be arranged to yield the empirical value for $g_{\text{A}}(\text{n}\to\text{p})$, eg by taking $b_1=b_2$.

Table 3. qqqq$\bar{\text{q}}$ configuration magnetic moments.

	proton	neutron	
$[31]_{\text{X}}[4]_{\text{FS}}[22]_{\text{F}}[22]_{\text{S}}$	0	1/3	
$[31]_{\text{X}}[4]_{\text{FS}}[31]_{\text{F}}[31]_{\text{S}}$	2/9	$-2/9$	qqqq : $J=1$
$[31]_{\text{X}}[4]_{\text{FS}}[31]_{\text{F}}[31]_{\text{S}}$	$-1/3$	0	qqqq : $J=0$
$[4]_{\text{X}}[31]_{\text{FS}}[22]_{\text{F}}[31]_{\text{S}}$	7/27	$-23/27$	$\bar{\text{q}}$: $J=3/2$
$[4]_{\text{X}}[31]_{\text{FS}}[22]_{\text{F}}[31]_{\text{S}}$	$-4/27$	0	$\bar{\text{q}}$: $J=1/2$
$[4]_{\text{X}}[31]_{\text{FS}}[31]_{\text{F}}[22]_{\text{S}}$	$-2/9$	0	
$[4]_{\text{X}}[31]_{\text{FS}}[31]_{\text{F}}[31]_{\text{S}}$	$-19/27$	1/9	$\bar{\text{q}}$: $J=3/2$
$[4]_{\text{X}}[31]_{\text{FS}}[31]_{\text{F}}[31]_{\text{S}}$	508/729	$-95/729$	$\bar{\text{q}}$: $J=1/2$

5 The strangeness form factors

A combined analysis of the empirical data on the s$\bar{\text{s}}$ contributions to the strangeness electric, magnetic and axial vector form factor has indicated that G_{E}^{s} is very small and negative, G_{M}^{s} is positive and G_{A}^{s} (as determined by neutrino scattering) is negative and that its value at $Q^2=0$, which represents the strangeness contribution to the proton spin, falls between -0.03 and -0.1 [23]. The most recent QCD lattice calculations do however give a very small positive value for G_{E}^{s} at $Q^2=0.1$ GeV^2 and a small and negative value for G_{M}^{s} at $Q^2=0.23$ GeV^2 [24, 25]:

$$\begin{aligned} G_{\text{E}}^{\text{s}}(0.1) &= 0.001\pm0.004\pm0.004, \\ G_{\text{M}}^{\text{s}}(0.23) &= -0.034\pm0.021\mu_{\text{N}}. \end{aligned} \tag{3}$$

These values are very close to the most recent values found experimentally by the A4 collaboration [4]:

$$\begin{aligned} G_{\text{E}}^{\text{s}}(0.22) &= 0.050\pm0.038\pm0.019, \\ G_{\text{M}}^{\text{s}}(0.22) &= -0.14\pm0.11\pm0.11\,\mu_{\text{N}}. \end{aligned} \tag{4}$$

These values also agree well with the recent lattice calculation of these two form factors [26].

Phenomenologically a negative value for G_{M}^{s} can be interpreted as arising from the longest range strangeness fluctuation into a kaon-hyperon loop, as that is associated with spin flip [27]. A positive value would on the other hand have to arise from strangeness fluctuation of shorter range as a loop, with a K^*-K transition [28].

There only 2 possible uuds$\bar{\text{s}}$ configurations in the proton, which are consistent with negative values for the $\mu^{\text{s}}=G_{\text{M}}^{\text{s}}(0)$ and $\Delta^{\text{s}}=G_{\text{A}}^{\text{s}}(0)$ [29]. In these configurations the $\bar{\text{s}}$ is in the P-state, while the uuds subsystem is spatially symmetric, with mixed spin-flavor symmetry $[31]_{\text{FS}}\{[211]_{\text{F}}[22]_{\text{S}}\}$ or $[31]_{\text{FS}}\{[31]_{\text{F}}[22]_{\text{S}}\}$. In both of these the relation:

$$\mu^{\text{s}}=\Delta^{\text{s}} \tag{5}$$

holds.

6 Pentaquarks

While there are presently no confirmed experimental signatures for pentaquarks, there s good reason to assume that such may exist, especially in the case of heavy flavors, where they may fall below the threshold for strong decay [30–32].

Pentaquarks appear naturally in chiral soliton models, which are consistent with the large color limit of QCD. Phenomenologically they recommend themselves in their ability to describe the low lying baryon spectrum, and in particular the description of the splitting of the $\Lambda(1405)$–$\Lambda(1520)$ negative parity doublet [33, 34], which cannot be explained in the basic qqq quark model [35]. In the soliton models the lowest energy pentaquarks have positive parity, while the original quark model based prediction assumed that all constituent in the pentaquark are in the orbital ground state, which implies negative parity [30, 31].

The first search for the charm-strange pentaquark did see a statistically insignificant structure at the energy 2860 MeV [36], close to the corresponding prediction by the bound state version of the Skyrme model [32], no empirical confirmation has appeared. The situation is in this sense similar to the lack of confirmation of the signal for a strange ("θ") pentaquark [37] near 1530 MeV [6].

The bound state version of the Skyrme model, which predicts narrow heavy flavor pentaquarks, also gives a good description of the low lying Λ and Σ hyperon resonances [38]. In this model the strange pentaquark will, however, have very large width as it lies above the threshold for strong decay [39]. It therefore does not match the conjecture of a very narrow strange θ pentaquark.

Empirical confirmation of any of these predicted pentaquarks, and of their parity, would be very instructive for elucidation of the structure of the baryons.

7 Nucleon form factors

The nucleon electromagnetic form factors are smooth functions of Q^2 over the hitherto measured range of values. The relative sharp fall off with Q^2 of the electric form factor of the proton G_E^p might however be an indication of a node somewhere in the region of $Q^2 \sim 10$ GeV^2 [40, 41]. If G_E^p is found to have a node in this region it can be a consequence of the presence of multiquark configurations, although it appears already in the covariant version of the qqq model in the case of front form kinematics [42].

This question was investigated on the basis of a simple model wave function with qqq and qqqq$\bar{\text{q}}$ components, the parameters of which were determined by a fit to the electric form factor of the neutron G_E^n, which vanishes in the non-relativistic qqq quark model in Ref. [43]. That model does indeed lead to a zero in G_E^p in the region $Q^2 \sim 10$–11 GeV^2.

In covariant models for the qqq system the neutron electric form factor takes small positive values as a consequence of the boosts from the rest frame to the Breit frame . If in addition a mixed symmetry $S-$ state component with 1%–2% probability is included in the wave function the calculated values for G_E^n agrees well with the empirical values [42]. Such a state naturally appears as a consequence of the spin dependence of the hyperfine interaction between the constituent quarks, in close analogy to the situation in the trinucleons, where that (small) component plays a crucial role eg. in radiative neutron capture on the deuteron.

8 Conclusions

Apart from the experimental evidence for flavor asymmetry in the proton [1] all other evidence for qqqq$\bar{\text{q}}$ components in the proton remains indirect. The backward versions of the G0 and A4 experiments may settle the issue of whether the strangeness form factors of the proton are not consistent with 0 and their signs. A confirmation of the still enigmatic possible pentaquark signal reported in Ref. [6] would be most welcome, but appears as unlikely. Precision measurement of the electric form factor of the proton in the region $Q^2 \sim 6$–12 GeV^2 will of great significance for delineating the range of phenomenological applicability of the basic qqq quark model.

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