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New quark relations for hadron masses and magnetic moments: A challenge for explanation from QCD

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Abstract

Prompted by the recent surprising results in QCD spectroscopy, we extend the treatment of the constituent quark model showing that mass differences and ratios have the same values when obtained from mesons and baryons. We obtain several new successful relations involving hadrons containing two and three strange quarks and hadrons containing heavy quarks and give a new prediction regarding spin splitting between doubly charmed baryons. We provide numerical evidence for an effective supersymmetry between mesons and baryons related by replacing a light antiquark by a light diquark. We also obtain new relations between quark magnetic moments and hadron masses. Limits of validity of this approach and disagreements with experiment in properties of the Σ and Ξ baryons are discussed as possible clues to a derivation from QCD.

1. Introduction

1.1. What is a constituent quark?

Nature tells us in experimental data that mesons and baryons are made of the same building blocks, sometimes called "constituent quarks". Mesons are two blocks and nothing else, baryons are three blocks and nothing else, and no present theory tells us what they are.

The challenge for QCD is to explain the structure of these blocks in quarks, antiquarks and gluons and why they are the same in mesons and baryons.

Early evidence that mesons and baryons are made of the same building blocks appeared in the remarkable successes of the constituent quark model. Static properties, low lying excitations and total scattering cross sections of both mesons and baryons are described as simple composites of asymptotically free quasiparticles with given effective masses [1–5].

The last few years have brought a rich crop of surprises in QCD spectroscopy [6]. These include too many experimental results relating mesons and baryons to be an accident. Their explanation remains a challenge for QCD [7–9]. Some of the new states seen have not been predicted at all; others are exceedingly narrow with properties very different from most theoretical expectations. This has prompted us to re-examine several aspects of the constituent quark model, to extend the experimental basis for simple meson–baryon relations and to search for clues to the eventual description by defining the domain where the simple model succeeds and where it fails.

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Extending these mesons–baryon relations to include heavy quarks shows that the simple constituent quark relations hold in some cases and break down in others. They hold between mesons that are bound states of a quark of any flavor and a color antitriplet light antiquark fermion, and baryons that are bound states of a quark of the same flavor and a color antitriplet light diquark boson, for all quark flavors. They seem to break down for states containing more than one heavy or strange quark.

Thus the QCD interaction between a color triplet heavy quark and a color antitriplet light quark system appears not to be sensitive to the structure of the light quark system; i.e. whether the color antitriplet is an antiquark or a color antitriplet ud pair. This suggests some kind of effective supersymmetry between hadrons related by replacing a light fermion by a light boson. The question arises whether these relations are obtainable from any of the known approaches to QCD or come from an effective light quark supersymmetry which is yet to be derived from QCD. So far the experimental evidence is impressive, and none of the various approaches to QCD seem to incorporate this symmetry. This is a very exciting challenge for theory.

The relation between the *constituent quarks* and the fundamental fields appearing in the QCD Lagrangian, the *current quarks*, remains to be understood. Perhaps there is no such relation and the success of the constituent quark model in relations between mesons and baryons is only a key to a hidden diquark–antiquark symmetry or effective supersymmetry.

Until now, lattice QCD is the only theoretical approach which starts from the fundamental fields of QCD and computes the spectrum. Despite this, many phenomenological relations between observables are hard to understand within the framework of lattice QCD, while they appear natural in the constituent quark model. This is why the elucidation of the relation between the effective and fundamental degrees of freedom is so important.

The obvious approach of treating a constituent quark as a current quark, valence quark or "bare quark" surrounded by a cloud or "sea" of gluons, $q\bar{q}$ pairs or pions has been tried many times and failed. A major difficulty is explaining how the same cloud works for the constituent quarks in both mesons and baryons. There are also sea quark effects which are known to be important for magnetic moments [10]. The constituent quarks somehow automatically incorporate such effects. What is missing and what we are unable to do at this stage is a theoretical derivation of such effects *from first principles* and their incorporation into the quark model.

Gell-Mann has suggested that constituent quarks are related to current quarks by a unitary transformation. However no such unitary transformation has been found. It may well be as complicated as the transformation between the electrons in QED and the quasiparticles needed to explain the fractional quantum Hall effect. Or it may not exist at all and merely be manifestation of a hidden effective supersymmetry.

We search for further illumination on this question by pursuing the successes and failures of the simple constituent quark model in unambiguous predictions of experimental data which can be clearly shown to be either right or wrong without adjusting free parameters.

1.2. Some simple successes

The successes of the constituent quark model in explaining regularities in experimental data that are not explained by other approaches are already too extensive to be dismissed as accidental. For example, calculations from experimental baryon masses and from meson masses give the same values ±3% for the effective quark mass difference $m_s - m_u$ between the strange and up quarks and their mass ratio m_s/m_u. QCD calculations have not yet succeeded to explain these striking experimental facts. The search for some QCD model for the structure of the constituent quark or a unitary transformation or effective supersymmetry is therefore of interest.

We search for clues to this structure or transformation by extending the domain where the simple model works as far as possible, while noting also the limits of its validity. One remarkable success of this model is its prediction [11] of the absolute value of the isoscalar nucleon magnetic moment [12] with no free parameters.

$$\mu_p + \mu_n = 2M_p \cdot \frac{Q_I}{M_I} = \frac{2M_N}{M_N + M_\Delta} = 0.865 \text{ n.m.} \quad (\text{EXP} = 0.88 \text{ n.m.}), \tag{1.1}$$

where $Q_I = \frac{1}{2} \cdot (\frac{2}{3} - \frac{1}{3}) = \frac{1}{6}$ and $M_I = \frac{1}{6} \cdot (M_N + M_\Delta)$ denote the charge and mass, respectively, of an effective "isoscalar nonstrange quark".

This simple derivation of the isoscalar nucleon moment is remarkable for giving an absolute prediction, not merely a ratio. It sets a mass scale in remarkable agreement with experiment by simply stating that the isoscalar nucleon magnetic moment is the Dirac moment of an isoscalar quark with a charge of $(1/6)$ and a mass $(1/3)$ of the mean mass of the nucleon and the Δ; i.e. the mass of a three quark system with the hyperfine energy removed. This value for an "effective" quark mass originally proposed by Sakharov and Zeldovich [1] has led to many successful relations between hadron masses [1–3].

This one prediction assumes no specific spin couplings of the quarks; e.g. $SU(6)$, as in the ratio relations [13]. The total spin contribution to the magnetic moment of a system of three identical quarks coupled to total spin $1/2$ is rigorously equal to the magnetic moment of a single quark. Why this works so well and how this scale arises from a real theory is a challenge for QCD and is not easily dismissed as an accident.

Constituent quark predictions for the proton, neutron and Λ magnetic moments follow of a baryon model of three constituent quarks and nothing else with Dirac moments having effective masses determined uniquely from hadron masses. The success of