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A perspective on pentaquarks[*]

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Abstract. Recent discoveries of manifestly exotic, narrow baryon resonances present a fundamental challenge for our theoretical understanding of low-energy QCD. This is a brief survey of their interpretation, emphasizing the possibility that diquark correlations are centrally involved. Many predictions and suggestions for future directions follow from that idea.

1 Introduction

Recently several experimental groups have reported observation of a new, manifestly exotic (B=1, S=1) baryon resonance $\Theta^+(1540)$ [1,2,3,4,5,6].

The resonance seems unusually narrow ($\Gamma < 15$ Mev) for a particle in this mass range with open channels to strong decay. Shortly after the conference the NA49 group at CERN announced evidence for an additional narrow "cascade" exotic (B=1, Q=S=-2) Ξ^{--} and also Ξ^-, Ξ^0 with masses close to 1860 Mev [7,8]. (Particles of this kind were predicted in my talk, at the time it was delivered.) Since the simplest quark assignments consistent with the quantum numbers of Θ^+ and Ξ^{--} are $(udud\bar{s})$ and $(dsds\bar{u})$ respectively, these particles have come to be called "pentaquarks".

The discoveries of manifestly exotic particles, which have been sought for decades, clearly open a new chapter in strong interaction physics. How fundamental are they? What can we hope to learn?

Although the discoveries are striking, I don't think they are so peculiar as to require introducing new interactions or modifying QCD as the basic theory of the strong interaction. We don't know how to calculate the consequences of QCD accurately at low energy, in general. But we know that numerical solution of the equations works brilliantly in the dozen or so cases where it has been done; we know that the perturbation theory, with asymptotic freedom, works brilliantly at high energy; and we know that the basic theory is so tight conceptually that we don't have sensible ways to modify it, even if we wanted to. So it seems unlikely that we'll be driven to modify the basic equations of QCD or the standard model, and no one has suggested this seriously.

On the other hand these discoveries do offer us a golden opportunity to sharpen and expand our understanding of QCD itself. In that context, I will argue, they could well have major impact upon several of the most fundamental unresolved issues.

Let me remind you how opportunistic, or I might say schizoid, our conventional, pragmatic approach to hadron dynamics is.

When we do precision work, we use honest quantum field theory: either straight numerical integration of the full equations using computers and the techniques of lattice gauge theory, or perturbation theory when justified by asymptotic freedom. In relativistic quantum field theory the states of definite energy, such as protons and pions in QCD, appear to be very complicated. If we insist on trying to constructing them as states in Fock space (which, ultimately, we can't really do) we would expect to find coherent superpositions of states containing various numbers of quark-antiquark pairs and gluons. The proton structure function in deep inelastic scattering, if interpreted in constituent language, bears this out: there are in fact an infinite number of gluons and quark-antiquark pairs lurking at small x. So, in a different way, does treatment of pions as Nambu-Goldstone bosons of chiral symmetry breaking: these are collective modes, constructed as waves within a condensate of tachyonic quark-antiquark pairs.

Yet when we turn to practical spectroscopy, we find the literature is dominated by simple models based on essentially non-interacting quarks living in a mean field or bag. Singlet quark-antiquark pairs, gluons, and correlations are censored out or integrated into effective constitutent degrees of freedom. This sort of naïve quark model is easy to use and it organizes a lot of data pretty successfully, which is why it's useful and popular. But it's a dead end. Consideration of pentaquarks brings some serious shortcomings of the naïve quark model into sharp focus. By confronting them we may well reach a new level of understanding, and elucidate some old and important problems in strong interaction physics that so far have been "bypassed", rather than addressed, in QCD.

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2 Basic modeling choices

I'm going to be advocating a particular interpretation of the emerging physics, and I admit up front that it is by no means established or universally accepted. It does have the virtue of being readily falsifiable, so I expect that this talk will come to look either prescient or hopelessly misguided within a few years. In fairness I should say a few words about the leading alternatives, and how they can be distinguished.

One's first instinct might be to model the Θ^+ as weakly bound kaon-nucleon molecule. QCD allows KN to couple to $q^4\bar{q}$ configurations with wave functions that differ markedly in space, color, and spin from the KN scattering state. If we want to avoid introducing such effects explicitly, we have no choice but to describe KN scattering in the region of the Θ^+ in terms of non-relativistic potential scattering. Let's see where that leads. Attractive forces in the s-wave do not generate resonances. If they are attractive enough they produce bound states, if not, they modulate the phase of the scattering wave function smoothly. In higher partial waves attractive forces can generate resonances through interplay between attraction and the repulsive angular momentum barrier. The mass and width of the resonance are related through the range and depth of the potential. For a simple attractive potential with range 1 fermi, the width of a P-wave resonance 100 MeV above threshold is more than 175 MeV. To obtain a width of order 10 MeV we would have to adjust the range to about 0.05 fermi! Thus the observed parameters of the Θ^+ can't be fit without bringing in strong, short-range attraction, which would be inconsistent with everything we know about QCD.

The chiral soliton or Skyrme model has played an important role in stimulating the search for exotics [9]. Indeed, the initial experiments leading to the discovery of Θ^+ were stimulated by the suggestions of Diakonov, Petrov, and Polyakov. Their procedures have been criticized on theoretical grounds, however, and their original prediction for the mass of Ξ^{--} was far too large. There is considerable flexibility in the model, and it might be possible to accommodate the existing pentaquark phenomenology. But whatever it may say about pentaquarks the model touches only a very small subset of the resonances you find in the Particle Physics Booklet (it does not describe the ρ, for example), and seems to rely heavily on inessential aspects of QCD (that is, without very light quarks the Skyrme model ceases to exist, but most of QCD hardly changes). My feeling is that an approach based more directly on fundamental degrees of freedom in QCD is more likely to be fruitful — but who knows?

Now let's consider what the naïve (uncorrelated) quark model says about pentaquarks. In the uncorrelated quark model, in which all the quarks are in the ground state of a mean field, the ground state of $q^4\bar{q}$ has *negative* parity. The full $SU(3)_f \times SU(2)_{\text{spin}}$ content of this multiplet and bag model estimates of masses and decay couplings can be found in a 1979 paper by Strottman [10]. This picture in no way explains the narrowness of the observed pentaquarks. There are very many states in flavor $\mathbf{1}_f$, $\mathbf{8}_f$, $\overline{\mathbf{10}}_f$, $\mathbf{27}_f$, *etc.*. The lightest have quark content $uudd\bar{d}$ and $uudd\bar{u}$ and would be expected to lie below the Θ^+. There is no evidence for a $\frac{1}{2}^-$ nucleon in this well explored region of the non-strange baryon spectrum. Furthermore, all the known light negative parity baryons are well described as orbital excitations of q^3. Altogether, the uncorrelated model of pentaquarks appears to be extremely problematic, on empirical grounds.

It is worth re-emphasizing that the uncorrelated quark model, where all the quarks are in the ground state of a mean field, assigns the ground state of $q^4\bar{q}$ (and therefore Θ^+ and Ξ^{--}), *negative* parity. Both the correlated quark model I'll be advocating and the chiral soliton model predict positive parity. The experimental verdict on this crucial issue is not yet in.

3 Diquarks

Attraction between quarks in the color $\bar{\mathbf{3}}_c$ channel has profound roots in microscopic QCD. Indeed, by bringing quarks together in this channel one halves the magnitude of their effective charge, and thus largely cancels the associated field energy. More particularly, the strongest attraction is in the flavor antisymmetric $J^P = 0^+$ channel. This channel is also favored by instanton-mediated interactions. At high baryon number density one can calculate rigorously that this is the channel in which quark Cooper pairs condense, to produce color superconductivity and color-flavor locking.

From now on, when I refer to diquarks I shall always have this color and flavor $\bar{3}_f$, $J^P = 0^+$ channel in mind and use the symbol $\boldsymbol{Q}$ for it.

In vacuum of course the quark-antiquark color singlet flavor singlet channel is even more attractive than the diquark. Condensation in the $\bar{q}q$ channel, which drives chiral symmetry breaking, supersedes condensation in the diquark channel. Nevertheless some suggestive signs of diquark attraction have occasionally been discerned. Perhaps the most compelling, and in any case the most immediately relevant concern exotic spectroscopy:

- The nearly ideally mixed nonet of $J^\Pi = 0^+$ meson including $f_0(600)$, $\kappa(800)$, $f_0(980)$, and $a_0(980)$ have always posed classification problems for conventional quark models. In particular, their mass spectrum is inverted, and there is an entire additional nonet of scalar mesons in the 1100–1500 MeV range, where $q\bar{q}$ mesons would be expected to lie. It is tempting to classify the light nonet as $qq\bar{q}\bar{q}$, with the quarks and antiquarks organized into $\boldsymbol{Q}$ and $\overline{\boldsymbol{Q}}$ respectively.
- The observed *absence* of manifestly exotic $qq\bar{q}\bar{q}$ mesons is a remarkable fact in itself. It is explained by the correlation of quarks into diquarks, since the product of diquark and antidiquark produces the same flavor quantum numbers as quark times antiquark. Without correlations, of course, many exotic representations are possible.
- There's a similar story for light-quark baryons made from four quarks and an antiquark. *A priori* there

are all sorts of possibilities for light exotics. But the only exotics observed belong (presumably) in the Θ^+ antidecuplet. Where are the others? Without correlations, it's a puzzle. Diquark correlations single out the observed antidecuplet uniquely. Since diquarks are $SU(3)$-flavor antitriplets, the only way to make an exotic out of two diquarks and an antiquark is to combine the diquarks symmetrically in flavor, $[\overline{3}_f \otimes \overline{3}_f]_{\mathcal{S}} = \overline{6}_f$, and then couple the antiquark. The flavor content of the resulting $q^4\overline{q}$ states is then $\overline{6}_f \otimes \overline{3}_f = 8_f \oplus \overline{10}_f$. Note that the antidecuplet comes together with an octet, which should mix when possible to produce pure strange quark content (ideal mixing).

- Other approaches to exotic spectroscopy predict a much richer spectrum of exotics including 27_f and 35_f multiplets. A notable difference is the absence in the diquark picture of an isovector analog of the $\Theta^+(1540)$, with $S = +1$ and charges $Q = 0$, 1, and 2. This state occurs in the 27_f and other exotic multiplets, but not in the $\overline{10}_f$. Its occurrence, with low mass, appears to be a robust prediction of chiral soliton models [11]. Targeted searches have come up empty [12].

4 Pentaquarks

My original discussion of detailed pentaquark phenomenology, which was essentially a sketch of [13], is already out of date due to the discoveries reported by NA49 — which are broadly consistent with it, but of course more specific and richer in detail. Since the situation is developing rapidly, here I will only mention a few salient points. For more on the interpretation of NA49, including suggestions for additional observables, see [14].

The exotic antidecuplet baryons should have spin-parity $1/2^+$ and be accompanied by nearby states with $J^\Pi = 3/2^+$ [13,15]: $[\boldsymbol{Q} \otimes \boldsymbol{Q}]_{\mathcal{S}}$ must be in the p-wave to satisfy Bose statistics. This $\ell = 1$ system can couple to the antiquark to give either $J^\Pi = 3/2^+$ or $1/2^+$. At present both possibilities are open for the cascades found by NA49.

The mass splittings of the $[\boldsymbol{Q} \otimes \boldsymbol{Q}]_{\mathcal{S}} \otimes \overline{q}$ octet and antidecuplet baryons, computed to first order in m_s, yield a spectrum discussed in detail in [13]. We would like to identify the Θ^+ with the $\boldsymbol{Q}\boldsymbol{Q}\overline{q}$ state $[ud]^2\overline{s}$. The narrowness of the physical Θ^+ can be explained by the relatively weak coupling of the K^+n continuum to the $[ud]^2\overline{s}$ state from which it differs in color, spin and spatial wave functions.

$N([ud]^2\overline{d})$ is the lightest particle in the $\mathbf{8}_f + \overline{\mathbf{10}}_f$. It has the quantum number of the nucleon. It is tempting to identify this state with the otherwise perplexing Roper resonance, the $N(1440)$ P_{11}, which has defied classification for decades. The $N(1440)$ is much broader than the Θ^+. Of course the internal structure and group-theoretic properties of Θ^+ and $N(1440)$ are quite different, and the $N(1440)$ can mix with the ordinary nucleon.

Most remarkably, we expect *two* multiplets of cascades for each spin. These are an $I = 3/2$ quartet arising from the decuplet, which includes the manifestly exotic $\Xi^+(uuss\overline{d})$ and $\Xi^{--}(ddss\overline{u})$; and an $I = 1/2$ doublet with charges 0, -1. This is important because, as argued in [14], it is difficult to accommodate the NA49 observations using an antidecuplet alone. Because these states differ in isospin, mixing between them should be quite small, barring extreme accidental degeneracy.

Charm and bottom analogues of the $\Theta([ud][ud]\overline{s})$ with quark content $[ud][ud]\overline{c}$ and $[ud][ud]\overline{b}$ might be stable against strong decay. The strong decay thresholds for these states depend on the corresponding pseudoscalar meson masses, which grow like the square root of the quark masses. Thus, for example, the threshold for $\Theta^0_c([ud][ud]\overline{c}) \to pD^-$ is relatively higher than the threshold for $\Theta^+_s(uudd\overline{s}) \to nK^+$ [13].

5 Future directions

Clearly, the first order of business must be to clarify and solidify the experimental situation. There is a host of predictions to check: positive parity; a crowded 4-component spectrum of light pentaquarks including nearby spin 1/2 and 3/2 flavor octet and antidecuplet multiplets; and narrow, possibly strongly stable exotics containing heavy antiquarks. Although I call this spectrum "crowded" you should recognize that it is far sparser in exotics than what is suggested by the uncorrelated quark model, or in implementations of the chiral soliton idea.

On the theoretical side, one important direction is to bring the power of lattice gauge theory to bear on these issues. Here the most obvious challenge is to find the pentaquarks. If the diquark picture is on the right track, that won't be entirely trivial to do, for two reasons. First, it is complicated to construct sources that are well matched to pentaquarks. In particular, they must have a very particular color structure, and rather complicated spatial structure reflecting the relative p-wave.

In the diquark of interest the quarks are coupled antisymmetrically in color, spin, and flavor, to the $\overline{3}_f$, $\overline{3}_c$, $J = 0$ representations. Let q^{ai} be a quark Dirac field. a is an $SU(3)_f$ index; i is an $SU(3)_c$ index. Then define,

$$\boldsymbol{Q}_{ck} = \epsilon_{abc}\epsilon_{ijk}q^{ai}i\sigma_2 q^{bj} \tag{1}$$

where σ_2 is the usual Dirac matrix. Then $\boldsymbol{Q}_{ck}$ is in the representations required.

In our pentaquark model two diquarks are coupled antisymmetrically in color, to a 3_c, and symmetrically in flavor, to a $\overline{6}_f$. This double-diquark carries a covariant 3_c label, k, and a pair of covariant $\overline{3}_f$ labels, $\{ab\}$. Obviously

$$\mathcal{S}_{\{ab\}\{cd\}} = \frac{1}{2}(\delta_{ac}\delta_{bd} + \delta_{ad}\delta_{bc}) \tag{2}$$

couples two antiquarks with labels c and d to the symmetric representation labeled by the symmetric pair $\{ab\}$. So the pair of diquarks, properly coupled, is

$$\mathbb{D}^k_{\{ab\}} = \epsilon^{ijk}\mathcal{S}_{\{ab\}\{cd\}}\boldsymbol{Q}_{ci}\boldsymbol{Q}_{dj} \tag{3}$$

As it stands, this operator is identically zero when all the quarks are in the same eigenmode of some mean field (i.e.

if the Dirac field is replaced by a single creation operator), as a consequence of Fermi statistics. Therefore we must introduce a derivative, effectively giving the diquarks one unit of relative angular momentum

$$\mathbb{D}^{k,\mu}_{\{ab\}} = \epsilon^{ijk}\mathcal{S}_{\{ab\}\{cd\}}\left(\boldsymbol{Q}_{ci}(D^{\mu}\boldsymbol{Q}_{dj}) - (D^{\mu}\boldsymbol{Q}_{ci})\boldsymbol{Q}_{dj}\right) \quad (4)$$

Note the minus sign between the two terms, chosen to produce a unit of relative angular momentum between the diquark pairs. The covariant derivative, D^{μ}, is in the $\overline{3}$ representation of color in order that the field $(D^{\mu}\boldsymbol{Q})$ transforms as an $\overline{3}$

$$D^{\mu} = \partial^{\mu} - ig\lambda^{\dagger}_{\ell}A^{\mu\ell} \quad (5)$$

The coupled diquarks transform like a Lorentz vector. This vector can be coupled to an antiquark to form baryon fields with angular momentum 1/2 or 3/2. It is simple to construct the appropriate Lorentz representations out of general vector, V^{μ}, and a Dirac spinor q. The spin 1/2 field is $V^{\mu}\gamma_{\mu}q$ and the spin 3/2 field is $V^{\nu}\sigma_{\mu\nu}q$. The only complication for us is that these baryons are built from an *antiquark* and two diquarks, so the correct forms are $B = V^{\mu}\gamma_{\mu}q_{\mathcal{C}}$ and $B_{\mu} = \sigma_{\mu\nu}V^{\nu}q_{\mathcal{C}}$, where $q_{\mathcal{C}} = \mathcal{C}\bar{q}^{\mathrm{T}} = i\gamma_2 q^{*}$. Altogether,

$$\begin{aligned} B_{\{ab\}d} &= \mathbb{D}^{k,\mu}_{\{ab\}}\gamma_{\mu}(q_{\mathcal{C}})_{dk} = \epsilon^{ijk}\mathcal{S}_{\{ab\}\{ef\}} \\ &\quad (\boldsymbol{Q}_{ei}(D^{\mu}\boldsymbol{Q}_{fj}) - (D^{\mu}\boldsymbol{Q}_{ei})\boldsymbol{Q}_{fj}) \\ &\quad \gamma_{\mu}(q_{\mathcal{C}})_{dk} \\ B_{\{ab\}d,\mu} &= \mathbb{D}^{k,\nu}_{\{ab\}}\sigma_{\mu\nu}(q_{\mathcal{C}})_{dk} = \epsilon^{ijk}\mathcal{S}_{\{ab\}\{ef\}} \\ &\quad (\boldsymbol{Q}_{ei}(D^{\nu}\boldsymbol{Q}_{fj}) - (D^{\nu}\boldsymbol{Q}_{ei})\boldsymbol{Q}_{fj}) \\ &\quad \sigma_{\mu\nu}(q_{\mathcal{C}})_{ck} \end{aligned} \quad (6)$$

Finally, the antidecuplet is projected out of these fields by symmetrizing over all the $SU(3)_f$ labels, a, b, and c. These are the sources we expect to couple well to pentaquarks. They bear little resemblence to the sources used in the first attempts to examine pentaquark spectra on the lattice.

Second, the diquark attraction is most effective for very light quarks, and these are difficult to handle numerically. Even the usual pseudoscalar mesons remain a challenge — one might say an embarrassment — for lattice gauge theory, for the same reason. One can simplify life somewhat, and also address an intrinsically interesting case, by specializing the antiquark to be a fixed color source.

These are significant technical problems, but I'm sure that ingenious people using powerful computers will overcome them.

A more open-ended challenge for lattice gauge theory is to look for diquark correlations more broadly, in the various contexts they have been suggested. By probing how strongly the light scalars, or for that matter nucleons, couple to different kinds of sources we can see if there is evidence for significant diquark content, for example.

On the more phenomenological side, it should be useful and instructive to consider expanding nonrelativistic quark or (better) bag models to include fundamental diquark degrees of freedom, with appropriate interactions, to see whether several different sectors (e.g., the scalar nonet and its heavy cousins light and heavy pentaquarks) can be described in a common semi-quantitative framework.

It is also tempting to speculate more freely. Is the reason for "hard core" repulsion between nucleons the short-range repulsion between the diquarks they contain? Is the reason for the $\Delta I = 1/2$ rule that the piece of the non-leptonic weak Hamiltonian that contains diquark quantum numbers is enhanced? Can we put the study of quark correlations using electroweak scattering probes, which already has been interpreted as providing evidence for diquarks in nucleons, on a rigorous footing?

Finally, I'd like to make two brief remarks of a theoretical nature:

1. By gauging flavor SU(2) strongly, one could enforce strong diquark correlations. So there is a logically consistent limit in which the diquark picture is manifestly appropriate. The remaining question, of course, how much of its characteristic structure survives as we go away from that limit, by decreasing the extra gauge coupling. That might be an interesting avenue to explore numerically.
2. Important diquark correlations would seem to be against the spirit of conventional large N approaches to QCD. The crucial circumstance that two quarks can lower their color charge drastically by coming together is special to N=3.

Acknowledgements. We can look forward to a vigorous dialogue among traditional laboratory experiments, numerical quasi-experiments, and theoretical explorations. It should be great fun, and I'll be surprised if the outcome is not a better understanding of how the murkiest part of our fundamental theory of matter - i.e., low-energy QCD - really works.

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