

Comment on
“Valence QCD: Connecting QCD to the Quark Model”

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I criticize certain conclusions about the physics of hadrons drawn from a
“valence QCD” approximation to QCD.

Lattice QCD is not just useful as a technique for calculating strong interaction observables like the proton mass: it can also be used to help us *understand* QCD. This is the goal of the work described in Ref. [1]. Its authors present a field theory which they call “valence QCD” (vQCD) which they hope can be identified with the valence quark model. The key feature built into vQCD is a form of suppression of Z-graphs, *i.e.*, of quarks propagating “backward in time” [2]. The authors make sound arguments for the importance of trying to capture the essence of the quark model in a field-theoretic framework, and present some interesting results (both theoretical and numerical) on vQCD. This comment is not directed at the goals of vQCD but rather at certain conclusions about the physics of hadrons which the authors have drawn from their work which I consider unjustified. Foremost among these is the claim highlighted in their abstract that baryon hyperfine interactions are “. . . largely attributed to the Goldstone boson exchanges between the quarks. . . ” and not to standard one-gluon-exchange (OGE) forces [3,4].

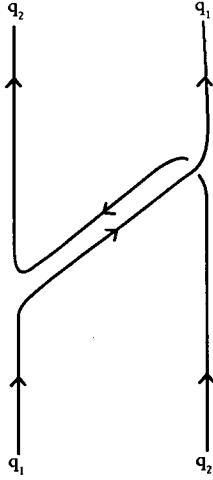


Fig. 1(a): Z-graph-induced meson exchange between two quarks.

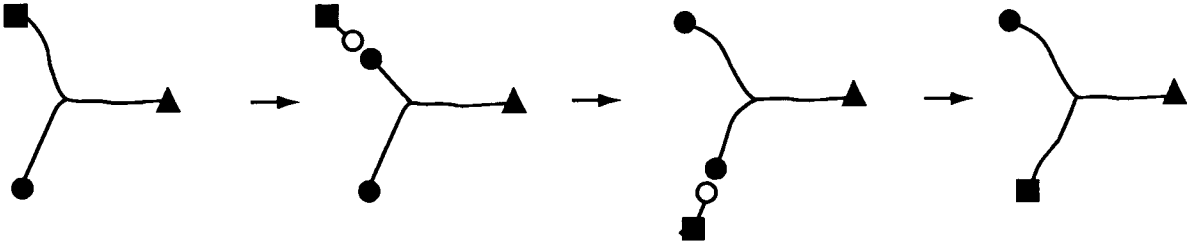


Fig. 1(b): A cartoon of the space-time development of the Z-graph-induced meson exchange in a baryon in the flux tube model. For diagrammatic clarity three different flavors of quarks are shown. Note that if the created meson rejoins the flux tube from which it originated, the produced $q\bar{q}$ pair can be of any flavor; however, such a process would be a closed $q\bar{q}$ loop and therefore not part of the quenched approximation. Also possible, but not shown, are OZI-violating graphs with the creation or annihilation of a disconnected $q\bar{q}$ meson; these are irrelevant to octet meson exchange in the SU(3) limit and enter in broken SU(3) only through the $\eta - \eta'$ mixing angle.

The origin of this claim is that in vQCD the $\Delta - N$ splitting is only about 50 MeV in contrast to the 180 MeV found on the same lattices in standard quenched QCD (qQCD) [5]. The authors of Ref. [1] argue that since vQCD differs from qQCD only in the suppression of Z-graphs, Z-graph-induced meson exchange between quarks (see Figs. 1), and in particular

the exchange of the octet of pseudoscalar mesons (OPE), must be the origin of most of the hyperfine interaction. My objection to this conclusion is that vQCD also appears to produce a very different spectrum (and thus, one presumes, very different internal hadronic structures) from qQCD, so that the reduced hyperfine *splittings* cannot necessarily be associated with a reduction in the strength of the hyperfine *interaction*. To see this we begin with an examination of the spectrum of vQCD, which I have extracted from Ref. [1] and display in Fig. 2 in comparison with the spectra of nature and of qQCD [6]. Most masses are rough estimates based on the graphs displayed in Ref. [1] and, except for the vQCD a_1 mass, I have made no attempt to estimate statistical or systematic uncertainties of the lattice “data”. However, the problem displayed in Fig. 2 does not need such refinements to stand out clearly: the spectrum of vQCD is dramatically different from both qQCD and nature!

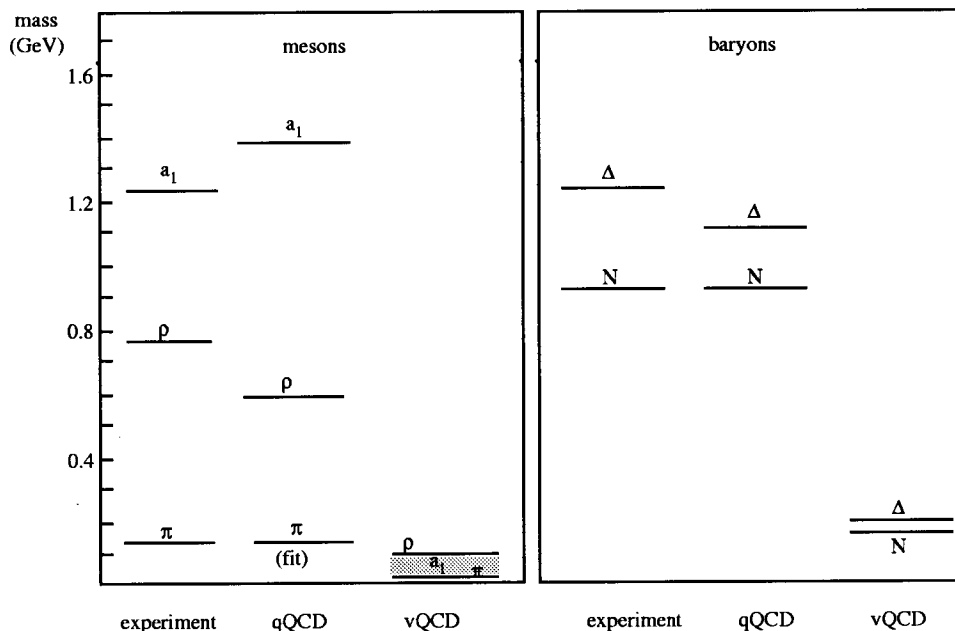


Fig. 2: The meson and baryon spectra of nature, quenched QCD, and valence QCD. I indicate by the shaded band an estimated error for the vQCD a_1 mass, since this mass is important to the arguments of the text.

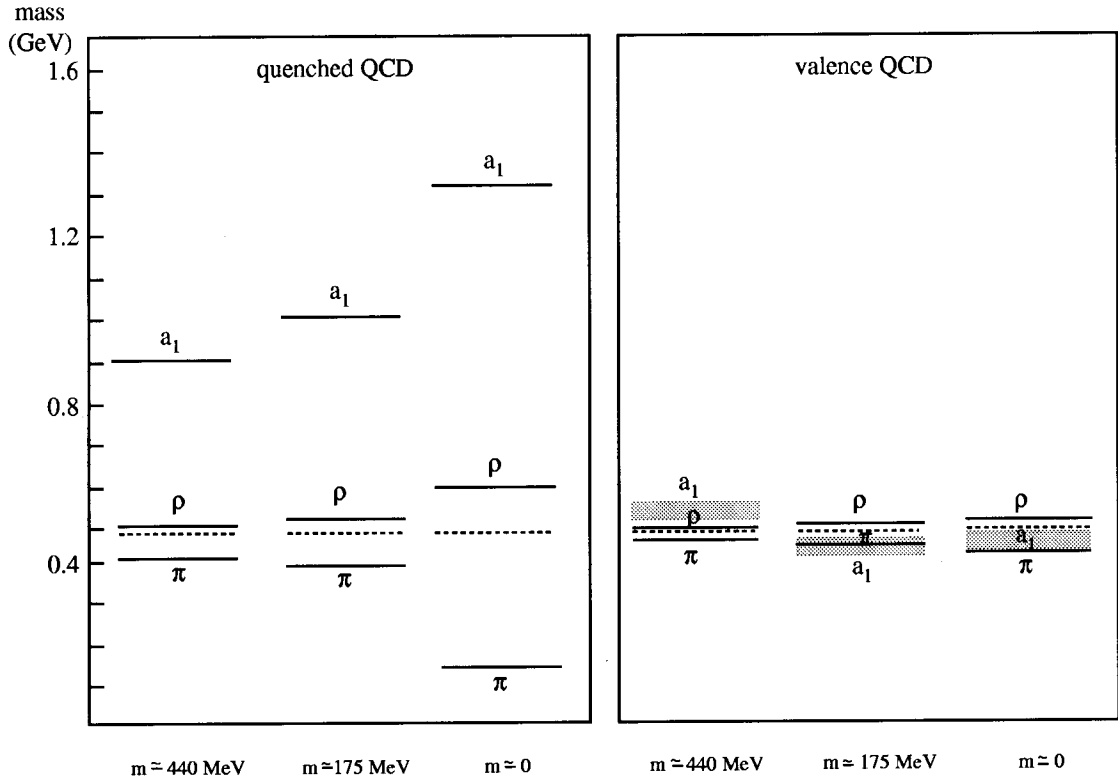


Fig. 3: The meson spectra of quenched QCD and valence QCD as functions of the quark mass m . The heavy quark center of gravity $\frac{1}{4}m_\rho + \frac{3}{4}m_\pi$ obtained from qQCD at $m = 440$ MeV is shown as a dotted line and is used to define an origin for all the other spectra, since it is the a_1 excitation energy relative to this center of gravity that is of interest here.

The authors of Ref. [1] argue quite cogently that the physical mechanisms which produce a constituent quark mass $m_{const} \simeq 300$ MeV in qQCD will be suppressed in vQCD, and proceed to analyze their results assuming that their spectra will be repaired by an overall shift of meson and baryon masses by $\sim 2m_{const}$ and $\sim 3m_{const}$, respectively. With this picture in mind, they conclude that the $\Delta - N$ hyperfine interaction in vQCD is much too small and are led to the conclusion quoted above. However, it is clear from Fig. 2 that such a simple shift of the spectral zeros cannot fix the vQCD spectrum: they would still have essentially zero orbital excitation energy (the $a_1 - \rho$ mass difference). At one point in the paper the authors mention the possibility of repairing the vQCD spectra by “tuning” the quark mass, though they never discuss this option. I have extracted their meson spectra for

heavier quark masses and plotted them in Fig. 3 for both qQCD and vQCD. The qQCD spectra are very reminiscent of the experimental spectra shown in Fig. 4, but vQCD appears to be very different even for relatively heavy quark masses. There is certainly no indication that quark masses $m \sim 300$ MeV, which fix the spectral zero problems in the mesons and baryons as expected, fix the problem of the vQCD excitation spectrum. The authors of Ref. [1] are silent on this matter.

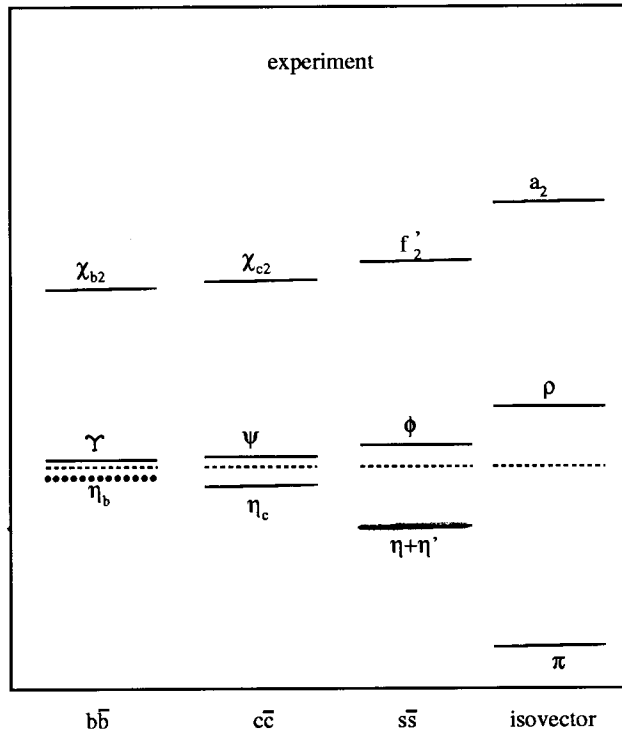


Fig. 4: The experimental spectra of $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, and isovector light quarkonia with the center of gravity of the S -wave mesons aligned. The 2^{++} states have been used in lieu of the 1^{++} states because ϕ_1 is not yet clearly identified. The pseudoscalar $s\bar{s}$ state (“ $\eta + \eta'$ ”) has been located by unmixing a 2×2 matrix assumed to consist of primordial $s\bar{s}$ and $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ states. The η_b is not yet discovered, but the theoretical prediction is shown as a dotted spectral line. The spectra are shown to scale, which may conveniently be calibrated from the $\chi_{c2} - \psi$ splitting of 459 MeV.

There is a complication in completing my criticism of Ref. [1]. The preceding discussion is focused on the meson spectrum because it is only for mesons that the orbital excitation

spectrum is given in Ref. [1]. Fig. 2 certainly gives the impression that vQCD has similar problems in both the meson and baryon sectors: in both the masses drop precipitously and the hyperfine interactions are much weakened. However, it is a logical possibility that the zeroth-order baryon and meson spectra have very different dynamical origins and that the baryon spectrum would be satisfactory after an overall shift (or tuning of m). In fact, even before showing us spectra, the authors of Ref. [1] show us lattice data on vQCD which indicates that the nucleons are of normal size, a result which suggests that the baryons are normal [7]. It would therefore certainly be interesting to know where the negative parity baryons are in vQCD. Let me note, however, that if the zeroth-order baryon and meson spectra have different physical origins, it would contradict much that we think we understand about QCD and would render such apparent empirical confirmation of that understanding as the equality of the slopes of meson and baryon Regge trajectories into misleading accidents. *If this were true, it would represent a far more profound conclusion than the ones the authors of Ref. [1] draw: it would destroy rather than just modify the quark model.* If vQCD eventually leads us to this result, it would thus make the other physics conclusions of Ref. [1] irrelevant. The simplest possibility is surely that the baryon excitation spectrum is as different from qQCD and nature as was the meson spectrum.

In summary, the spectrum of vQCD does not appear to represent a good approximation to nature, to qQCD, or to the quark model. This does not mean that we can't learn many things from it, but it does mean that one must be very cautious in drawing conclusions from vQCD. In particular, hyperfine splittings are normally especially sensitive functions of the internal structure of the states being perturbed (*e.g.*, in the nonrelativistic quark model they are proportional to the square of the spatial wave function at zero separation). There is certainly no reason to believe that a ground state system belonging to such a poorly described spectrum will have reasonable short distance matrix elements.

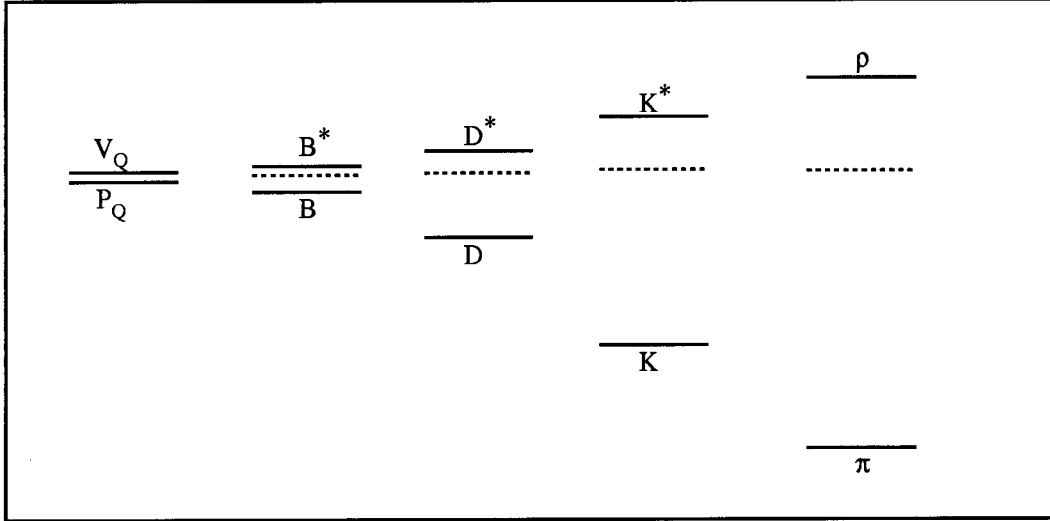
I would like to point out that independent of the basic objections I have raised to drawing physics conclusions from vQCD at this stage, the association of the missing hyperfine strength of vQCD with Goldstone boson exchange (OPE) between quarks suffers from some

serious problems. The first of these is apparent from Fig. 2: while qQCD describes both the $\rho - \pi$ and $\Delta - N$ splitting, they are both poorly described in vQCD. It would be natural and economical to identify a common origin for these problems. However, the Z -graph-induced meson exchange of Fig. 1(a) can only act between two quarks and *not* between a quark and an antiquark. Of course it is logically possible that there are different mechanisms in operation in the two systems but, as we will see, this is very difficult to arrange.

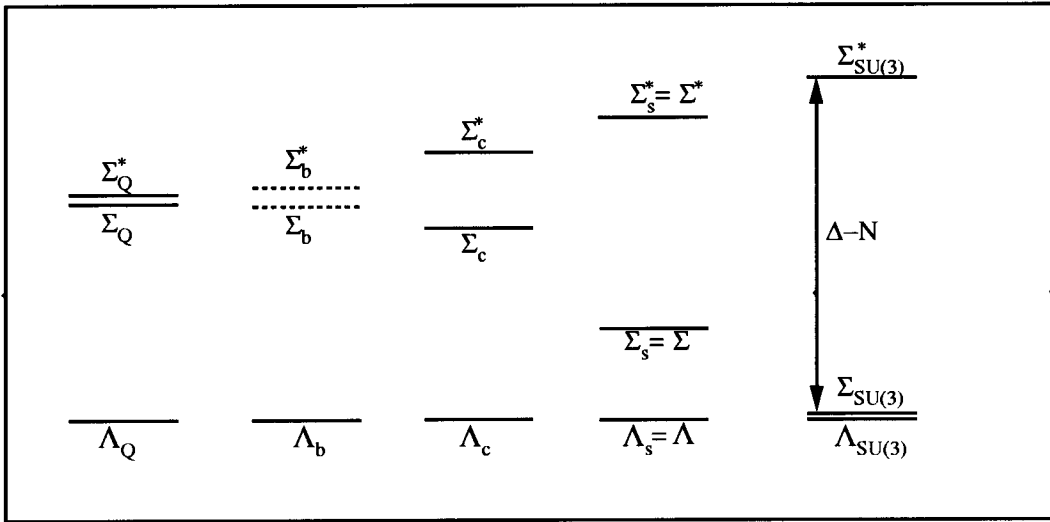
Figure 4 showed the evolution of quarkonium spectroscopy as a function of the quark masses. In heavy quarkonia ($b\bar{b}$ and $c\bar{c}$) we know that hyperfine interactions are generated by one-gluon-exchange (OGE) perturbations of wave functions which are solutions of the Coulomb-plus-linear potential problem. I find it difficult to look at this diagram and not see a smooth evolution of the wavefunction (characterized by the slow evolution of the orbital excitation energy) convoluted with the predicted $1/m_Q^2$ strength of the OGE hyperfine interaction.

This same conclusion can be reached by approaching the light quarkonia from another angle. Figure 5(a) shows the evolution of ground state heavy-light meson hyperfine interactions from the heavy quark limit to the same isovector quarkonia shown in Fig. 4. In this case we know that in the heavy quark limit [8] the hyperfine interaction is given by the matrix element of $\vec{\sigma}_Q \cdot \vec{B}/2m_Q$, consistent with the OGE mechanism and the striking $1/m_Q$ behaviour of the data on ground state splittings as m_Q is decreased from m_b to m_c to m_s to m_d .

Since the OPE mechanism cannot contribute here, the OGE mechanism is therefore certainly the natural candidate for generating all meson hyperfine interactions. The problem that arises for the OPE hypothesis is that it is then nearly impossible to avoid the conclusion that OGE is also dominant in baryon hyperfine interactions: the OGE $q\bar{q}$ and qq hyperfine interactions are related by a simple factor of 1/2, and given the similarities of meson and baryon structure (for example, their charge radii, orbital excitation energies, and magnetic moments are all similar), it is inevitable that the matrix elements of OGE in baryons and mesons are similar. This connection is explicitly realized in quark models [9].



(a)



(b)

Fig. 5: Ground state meson (a) and baryon (b) hyperfine splittings in heavy-light systems as a function of the mass m_Q of the heavy quark. The spectra on the far left are the $m_Q \rightarrow \infty$ limits of heavy quark symmetry. The $\Sigma_Q^* - \Lambda_Q$ splitting and the positions of Σ_b^* and Σ_b are estimates from the quark model; all other masses are from experiment. The spectra are shown to scale; the meson scale may conveniently be calibrated with the $D^* - D$ splitting of 141 MeV and the baryon scale with the $\Sigma_c - \Lambda_c$ splitting of 169 MeV.

There is another very serious problem with the OPE mechanism which surfaces in mesons. I have explained that there are no Z-graph-induced meson exchanges in mesons. However,

Fig. 6 shows how the same meson exchanges which are assumed to exist in baryons will drive OZI-violating mixings in isoscalar channels *via annihilation graphs*. I have argued above that the structure of mesons and baryons is so similar that it is impossible to avoid their having similar OGE matrix elements. The same is true for OPE matrix elements: it is impossible to maintain that OPE is strong enough to produce the $\Delta - N$ splitting in baryons without predicting a matrix element of comparable strength associated with Fig. 6 in mesons. Such matrix elements will violate the OZI rule [10]. To see this, consider the mixing between the pure ω -like state $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ and the pure ϕ -like state $s\bar{s}$. This mixing will be driven by kaon exchange and from the preceding very general arguments we must expect that the amplitude A_{OZI} for this OZI-violating process will have a strength of the same order as the 200 MeV $\Sigma^* - \Sigma$ splitting (which is also driven purely by kaon exchange). Empirically A_{OZI} is very tiny - - - of the order of 10 MeV - - - in all known meson nonets (except the pseudoscalars); amplitudes an order of magnitude larger would lead to dramatic violations of the OZI rule.

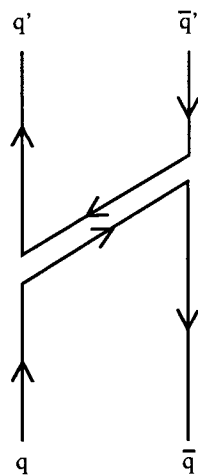


Fig. 6: OZI-violating mixing in isoscalar mesons *via* the exchange of a $q\bar{q}'$ meson.

The mesons thus produce some disastrous conclusions for the Goldstone boson exchange hypothesis. The first is the very unaesthetic conclusion that two totally distinct mechanisms are in operation producing meson and baryon hyperfine interactions: OGE in mesons and

OPE in baryons. The second is the virtual impossibility of having strong OGE matrix elements in mesons without also producing strong OGE matrix elements in baryons, in conflict with the basic hypothesis of that model. The third is that the OPE mechanism produces unacceptably large OZI violation in meson nonets.

As shown in Figure 5(b), experiment actually provides strong evidence in support of the dominance of OGE and *not* OPE in the baryons themselves! Fig. 5(b) is the baryon analog of Fig. 5(a) where once again one knows rigorously that the hyperfine interactions are controlled by the matrix elements of $\vec{\sigma}_Q \cdot \vec{B}/2m_Q$ for heavy quarks. It is clear from this Figure that in the heavy quark limit the OPE mechanism is not dominant: exchange of the heavy pseudoscalar meson P_Q would produce a hyperfine interaction that scales with heavy quark mass like $1/m_Q^2$, while for heavy-light baryons the splittings are behaving like $1/m_Q$ as demanded by heavy quark theory (with which the OGE mechanism is automatically consistent). It is difficult to look at this diagram and not see a smooth evolution of this $1/m_Q$ behaviour from m_c to m_s to m_d , where by SU(3) symmetry $\Sigma_{SU(3)}^* - \Lambda_{SU(3)} = \Delta - N$, the splitting under discussion here. One might try to escape this conclusion by arguing that between m_c and m_s the OGE-driven $1/m_Q$ mechanism turns off and the $1/m_Q^2$ OPE mechanism turns on. From the baryon spectra alone, one cannot rule out this baroque possibility. However, in the heavy-light mesons of Fig. 5(a) there is no alternative to the OGE mechanism, and since the $Q\bar{q}$ interaction continues to grow like $1/m_Q$ as m_Q gets lighter, so must the Qq interaction. I see no escape from the conclusion that OGE is dominant in *all* ground state hyperfine interactions.

The preceding discussion of the generic problems of the OPE mechanism was an extended digression designed to dampen any remaining enthusiasm for one of the highlighted conclusions of Ref. [1]. It is not logically connected to and should not distract the reader from the main argument presented in this Comment. Valence QCD is a potentially interesting field-theoretic approximation to QCD from which we could in principle learn a great deal about the physics driving hadron structure and dynamics. My criticisms of the conclusion extracted from vQCD in Ref. [1] about the physics of hyperfine interactions are based on

the fact that vQCD has a very different spectrum from qQCD and nature. It is thus unclear whether the reduced $\Delta - N$ splitting of vQCD is due to a diminished hyperfine interaction or a change in the short distance structure of the hadrons. Until it is better understood, vQCD must only be used with great care in drawing conclusions about the physics of hadrons.

ACKNOWLEDGEMENTS

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- [6] Ref. [1] also gives results for the a_0 . The scalar sector is so controversial and so poorly understood experimentally that I have focused on the a_1 , but no conclusion I have drawn depends on this selection.
- [7] A poor spectrum does not always lead to a poor description of the ground state. For example, the ground state of the Coulomb-plus-linear potential problem can in certain circumstances be dominated by the Coulomb region so that its gross properties are independent of the string tension, leaving only short distance effects like the hyperfine interaction sensitive to the slope of the linear potential.
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