Diquark properties from lattice QCD

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It has been argued recently that diquarks, a pair of quarks in the anti-triplet representation of SU(3) color, are important building blocks of baryons. The assumption that the scalar diquark is tightly bound seems to be nicely accommodated by experimental data. In this paper I attempt to extract phenomenological properties of diquarks from lattice QCD calculations. In particular, I use the MILC 2+1 dynamical fermion lattices with domain wall fermion valence quarks to probe diquarks very close to the chiral limit.

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1. Introduction

The possibility of the existence [1] of narrow width five quark hadronic states has excited a lot of theoretical and experimental activity with an aim at finding them and explaining their structure. A recent review of the experimental status of pentaquarks can be found in [2]. One model for the existence of such states has been put forward by Jaffe and Wilczek [3]. A central feature of this model is the existence of a tightly bound diquark.

The diquark, as its name signifies, is an object made out of two quarks. The color 3×3 is reduced to the symmetric 6 and the anti-symmetric anti-triplet $\bar{3}$ representations. It is not difficult to argue that the color anti-triplet representation is energetically more favorable that the symmetric one. Both one gluon exchange and the 'tHooft interactions are attractive in this channel. In what follows the term diquark is used to describe the color anti-triplet representation.

Simple phenomenological observations ranging from deep inelastic scattering to the QCD spectrum features indicate that not all diquarks are created equal. It has been argued that the anti-symmetric in flavor scalar diquark

$$q_f^a C \gamma_5 q_{f'}^b \varepsilon_{cab} \varepsilon^{ff'} \tag{1.1}$$

is energetically more favorable than the spin 1 diquark

$$q_f^a C \gamma_\mu q_{f'}^b \varepsilon_{cab} . \tag{1.2}$$

In the above f is a flavor index, while abc are color indices. The spin indices are suppressed. A model based on this assumption [4] seems to accommodate the mass hierarchies of the observed hadron spectrum.

Although the diquark is a seemingly simple object, it is difficult to ask questions about its properties outside the scope of a model. For that reason a lattice QCD calculation may be able to provide more information about its structure than real experimental data. In this paper I describe a calculation in Lattice QCD of the difference in binding energy between the vector and the scalar diquark. Two more papers in these proceedings discuss ways to address similar questions in the context of numerical calculations [5, 6].

2. The method

Measuring a mass for the diquark is not possible since it is a color non-singlet object that can only exist in a bound colorless state. Together with another quark it forms a baryon. So the mass difference of a baryon with the vector diquark (ex. Δ) from a baryon with the scalar diquark (ex. proton) can provide information on the binding energy splitting of these two diquarks. Unfortunately, spin dependent interactions of the quark and the diquark are also different for the two different spin configurations. Hence mass splittings of real baryons are not clean probes of the binding energy difference of diquarks. On the other hand, if the mass of the third quark is infinite, the spin dependent interactions drop out, allowing us to probe the binding energies of the diquarks.

We can easily construct baryons made out of an infinitely heavy quark and a diquark, on the lattice. The correlation function of such an object is

$$G_\Gamma(x,t;x,0) = \langle u^a(x,t)\Gamma d^b(x,t)\varepsilon_{cab}P^{cc'}(x,t;x,0)\bar{d}^{a'}(x,0)\Gamma \bar{u}^{b'}(x,0)\varepsilon_{c'a'b'}\rangle , \tag{2.1}$$
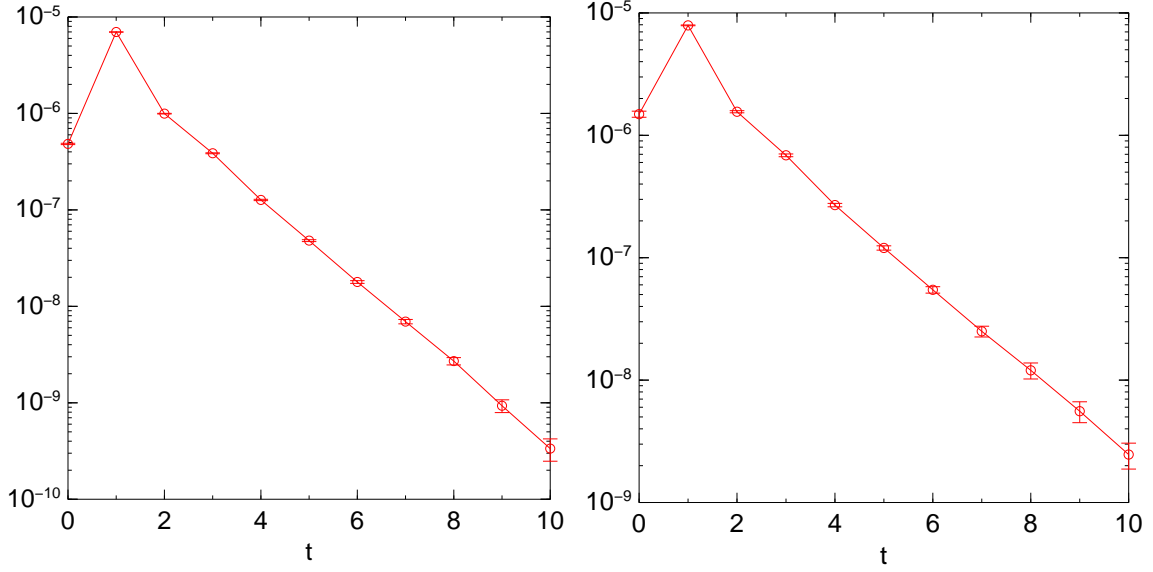
Figure 1: The Σ_Q (left) and Λ_Q (right) correlators for the staggered bare quark mass 0.010

where u and d are the light quark flavors and $P^{cc'}$ is the Wilson line connecting the source and the sink which are separated by time t. The spin matrix Γ is either $C\gamma_5$ or $C\gamma_\mu$ for the scalar and vector diquarks, respectively. The goal here is to calculate the lowest mass associated with the correlation functions $G_\Gamma(x,t;x,0)$ and compute the mass difference between the mass of the state with the scalar diquark (Λ_Q) and that of the mass of the sate with the vector diquark (Σ_Q). This mass difference is the difference in the binding energy of the two diquarks.

3. Lattice details

In order to perform the above calculation it is essential to use quark masses as light as possible. In addition, in order be able to obtain physically interesting results we performed the calculation with dynamical fermions. We used the 2+1 improved Kogut-Susskind (Asqtad) [7–9] fermion lattices at lattice spacing $a = 0.125$fm provided by MILC [10, 11]. The improved Kogut-Susskind action has been shown to have very good scaling properties [12, 13]. For the light quark propagators we use gauge invariant Gaussian smeared source propagators provided by LHPC. For details on the propagator generation see [14, 15]. The essential feature of these propagators is that the domain wall fermion mass has been tuned so that the pion mass matches the Kogut-Susskind Goldstone pion mass. In addition, HYP smearing has been used in order to improve the domain wall fermion explicit chiral symmetry breaking. Tests of the locality and the chiral behavior of the domain wall action have been performed and proved that the action is local and that the explicit chiral symmetry breaking is negligible as far as the relevant physical observables are concerned.

The number of configurations used range from 400 to 650 configurations depending on the ensemble. The calculation was performed for the bare light Kogut-Susskind quark masses 0.007, 0.010, 0.020 and 0.030. Since we are interested in the mass difference between the Λ_Q and Σ_Q
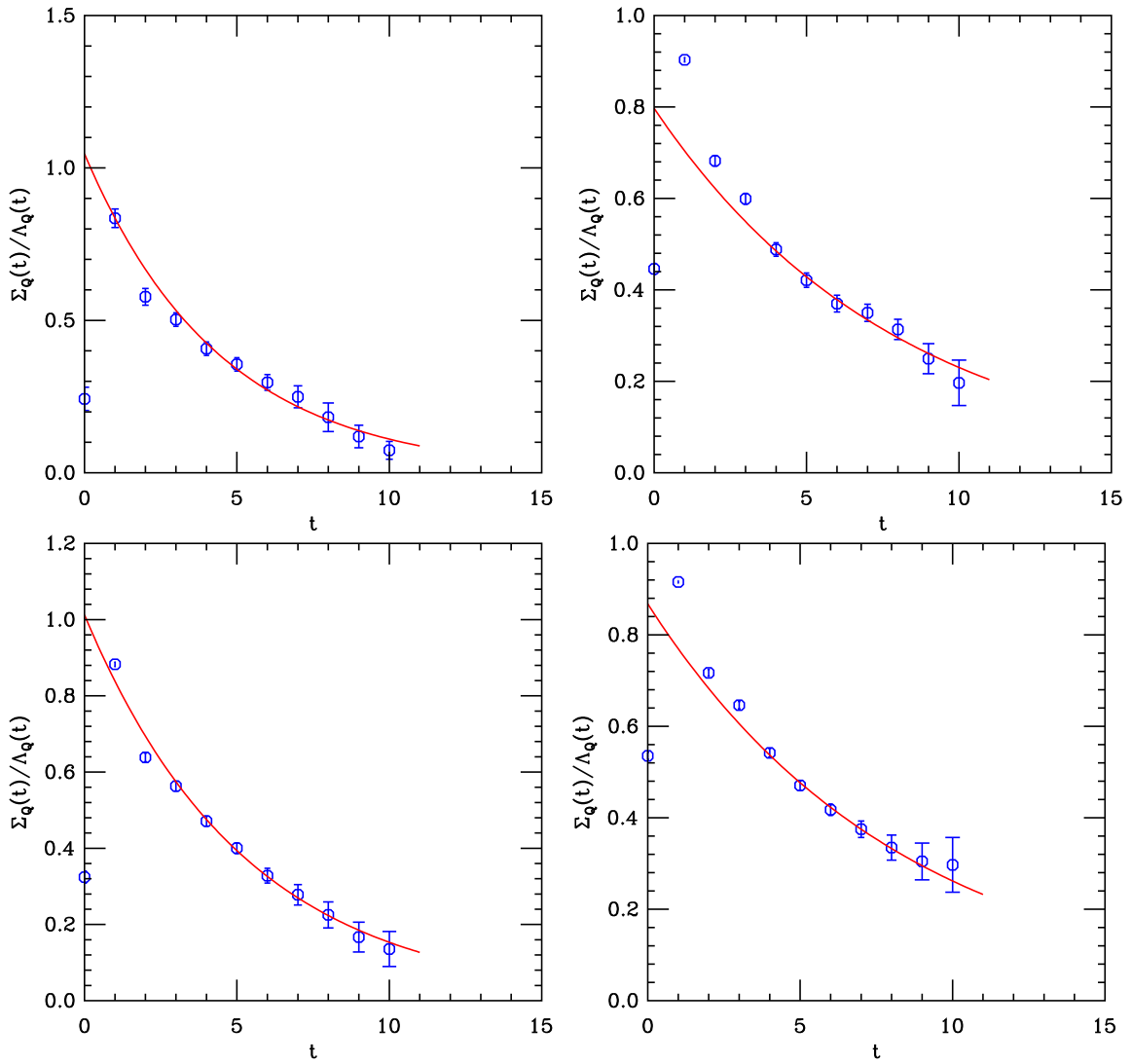
Figure 2: The ratio $R(t)$ for the staggered bare quark masses 0.007 (top left), 0.010 (top right), 0.020 (bottom left) and 0.030 (bottom right). The red lines are exponential fits in the time range 4 to 10.

states, we compute the ratio of the these two correlators

$$R(t) = \frac{G_{C\gamma_\mu}(t)}{G_{C\gamma_5}(t)} \ . \tag{3.1}$$

Then we fit this ratio to a simple exponential from which we extract the mass difference of the two low lying states. Jackknife analysis is used to perform the error estimates. For the scale, we used the $a = 0.125$fm. For all the fits, we chose the time range 4 to 10. The signal for time larger than 10 deteriorated rapidly. In Figure 1 we present a typical set of Λ_Q and Σ_Q correlators for the bare staggered sea quark mass 0.010. The ratios of correlators from which we extracted the diquark mass splittings are presented in Figure 2.
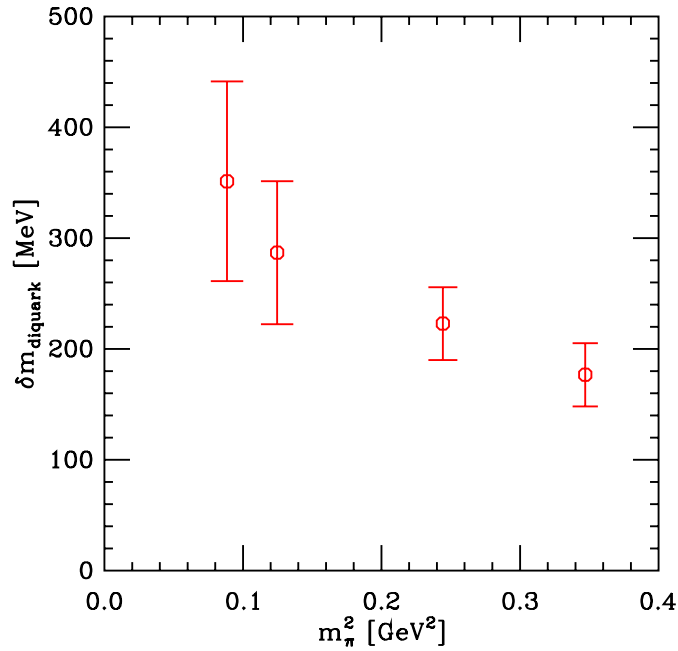
Figure 3: The diquark mass splitting in units as function of the pion mass squared.

4. Results and discussion

As we can see in Figure 3 the computed binding energy difference of the scalar and the vector diquark is a rather large number compared to QCD scales. A linear extrapolation to the chiral limit yields a value of $360(70)$MeV. The value of the splitting increases rapidly with decreasing quark mass providing evidence that scalar diquarks made out of light quarks are more favorable than those made out of heavier quarks. Note that all our quark masses are lower than the strange quark mass.

In this calculation I have not yet addressed carefully several sources of systematic errors such as continuum extrapolations, chiral extrapolations, scale setting and volume dependence. Nonetheless, it seems that all these errors should alter very little the basic features of these results: the binding energy of the the scalar diquark is fairly large and it increases rapidly with decreasing quark mass. Both these features are assumed in the Jaffe-Wilczek model of pentaquarks [3] and in Wilczek's picture of QCD spectrum [4]. Here I present a numerical justification for these assumptions.

Acknowledgments

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