

# Zero Temperature String Breaking with Staggered Quarks <sup>\*</sup>

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The separation of a heavy quark and antiquark pair leads to the formation of a tube of flux, or “string”, which should break in the presence of light quark-antiquark pairs. This expected zero-temperature phenomenon has proven elusive in simulations of lattice QCD. In an extension of work reported last year we present clear evidence for string breaking in QCD with two flavors of dynamical staggered sea quarks and apply our results to a simple three-state mixing model for string breaking. We find that mixing is weak and falls to zero at level crossing.

## 1. INTRODUCTION

The heavy quark-antiquark potential is known quite accurately in quenched simulations[1]. It is traditionally measured with the Wilson-loop observable, proportional to  $\exp[-V(R)T]$  at large  $T$ . In the presence of dynamical quarks it is expected that the potential levels off with increasing  $R$ , signaling string breaking. However, in QCD simulations string breaking has proven to be very difficult to detect with this observable, even out to  $R \approx 2$  fm[2,3].

The reason string breaking has not been seen using the traditional Wilson-loop observable has been apparent for some time [4–6]. The Wilson loop can be regarded as a hadron correlator with a source and sink state “F” consisting of a fixed heavy quark-antiquark pair and an associated flux tube. The correct lowest energy contribution to the Wilson-loop correlator at large  $R$  should be a state “M” consisting of two isolated heavy-light mesons. However, such a state

with an extra light dynamical quark pair has poor overlap with the flux-tube state, so it is presumably revealed only after evolution to very large  $T$ . To hasten the emergence of the true ground state, it is necessary to enlarge the space of sources to include both F and at least one M state.

String breaking has been demonstrated in the strong-coupling approximation to QCD [6,7], and a variety of QCD-like theories [8–13], and in SU(3) with dynamical quarks at nonzero temperature[5]. Last year, we reported a preliminary low-statistics result for two flavors of staggered quarks [14], and, earlier this year, Pennanen and Michael announced evidence for string breaking at zero temperature using Wilson-clover quarks and a novel technique for variance reduction in computing the light quark propagator [15]. This year we report results with higher statistics [16].

## 2. METHODOLOGY

We work with 198 configurations of size  $20^3 \times 24$ , generated with the one-plaquette gauge action

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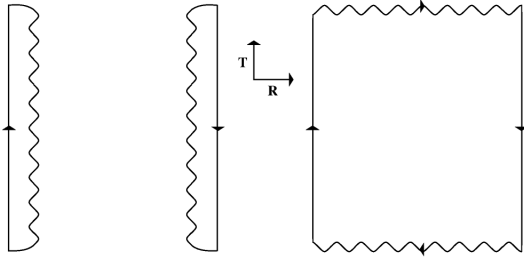


Figure 1. The static-light meson-antimeson pair contribution to the full QCD propagator. The wiggly lines denote the light quark propagator. Shown are the ‘direct’ and ‘exchange’ terms respectively.

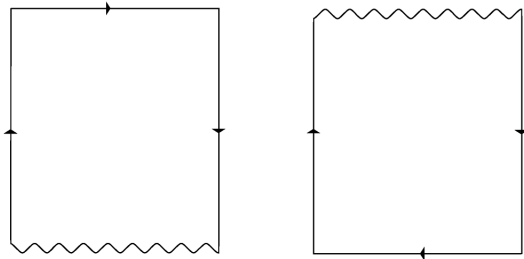


Figure 2. The string-meson correlation matrix element  $G_{FM}$  (and its hermitian conjugate  $G_{MF}$ ). The wiggly line again denotes the light quark propagator.

at  $6/g^2 = 5.415$  in the presence of two flavors of conventional dynamical staggered quarks of mass  $am = 0.0125$ . The lattice spacing (*via* the Sommer parameter [17]) is approximately 0.163 fm, and  $m_\pi/m_\rho = 0.358$ , giving a comfortable box size and a relatively light quark.

Our flux tube “F” source and sink operator is constructed from the product of smeared spatial links, for the most part taken along one of the lattice axes, using 10 APE smearing iterations [18], combining the direct link with a factor  $1 - \alpha$  (in our case,  $\alpha = 0.294$ ) and six staples with factor  $\alpha/6$  with SU(3) projection after each iteration. The correlator of this operator  $G_{FF}(R, T)$  is the familiar Wilson loop with smeared space-like segments, and point-like static quark and antiquark lines. Our two-meson source and sink operator “M” is the direct product of static-light meson

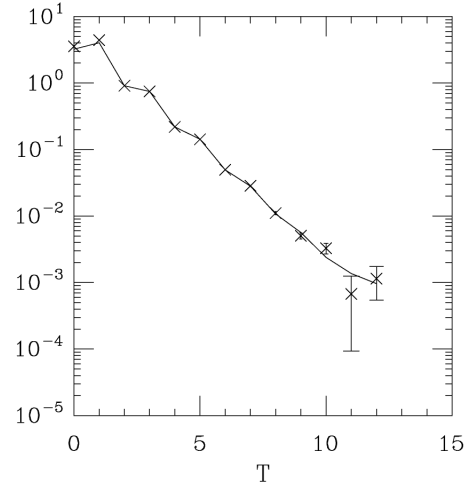


Figure 3. Static-light propagator with a nonoscillating  $S$ -wave and oscillating  $P$ -wave component. The solid line connects the best fit values.

and antimeson operators.<sup>1</sup> In constructing the static-light meson we use a light-quark wave function with weight 2 at zero separation and 1 on each of the six on-axis second neighbors. Thus we measure the additional correlation matrix elements  $G_{MM}(R, T)$ ,  $G_{MF}(R, T)$  and  $G_{FM}(R, T)$ , diagramed in Figs. 1 and 2. These observables are computed for all translational and cubic rotational displacements. The required all-to-all propagator is estimated using a random source technique with 128 random sources per configuration.

### 3. RESULTS

The static-light meson correlator in Fig. 3 has contributions from both a nonoscillating  $S$ -wave ( $B$ -meson-like) light-quark orbital and oscillating  $P$ -wave ( $B^*$ -meson-like) orbital with  $aE_S =$

<sup>1</sup>In the continuum limit the meson pairs created by this operator are in a combination of light quark singlet and nonsinglet states, and only the singlet part should mix with the flux tube. On our coarse lattice, where only one meson-meson state is important, this affects the overlap  $Z_M$ , but not the mixing parameters. In this analysis we have not attempted to reconcile the restriction to two flavors in internal quark loops with the flavor counting of the external states, which would affect the relative weights of the “direct” and “exchange” contributions to  $G_{MM}$ . With the accuracy we have achieved so far, this makes no detectable difference.

0.7884(12) and  $aE_P = 1.022(6)$ . Thus our two-meson correlator includes nonoscillating combinations  $SS$  and  $PP$  and an oscillating  $SP$ . If mixing is weak, our two-channel correlators should also include a flux-tube level with an approximately Coulomb-plus-linear behavior in  $R$ . Our fit ansatz for the two-channel correlator is

$$G_{AB}(R, T) = \sum_{i=1}^N Z_{Ai}^*(R) Z_{Bi}(R) [\lambda_i(R)]^{T+1}, \quad (1)$$

where  $A, B$  refer to the flux tube  $F$  or meson-meson  $M$  states and  $\lambda_i(R)$  is a real (positive or negative) eigenvalue of the transfer matrix. The channel energy is  $-\log(|\lambda_i(R)|)$ .

For simplicity we restrict the analysis to three spectral components

$$\begin{aligned} \lambda_1(R) &= e^{-V_1(R)} \\ \lambda_2(R) &= -e^{-V_2(R)} \\ \lambda_3(R) &= (-)^{R+1} e^{-V_3(R)}, \end{aligned} \quad (2)$$

corresponding in the unmixed language, respectively, to the  $SS$ ,  $SP$ , and flux-tube components. The peculiar phase for the flux tube component is required by discrete lattice symmetry and can be obtained simply by interpreting the Wilson loop as a heavy staggered quark loop.

Results for the three levels are plotted in Fig. 4. We see clear evidence for string breaking at the first level crossing (about 1 fm), but with our statistics, we see no evidence for rounding associated with avoided level crossing. Thus string-breaking pair-creation and annihilation transitions are weak in QCD.

To explore mixing further, we introduce a mixing model similar to that of Drummond, Pennanen and Michael[6,15].

$$G(R, T) = \tilde{Z}^0(R) \mathcal{T}(R)^{T+1} Z^0(R), \quad (3)$$

where the transfer matrix is given by

$$\mathcal{T}(R) = \begin{pmatrix} \lambda_1^0(R) & 0 & x \\ 0 & \lambda_2^0(R) & y \\ x & y & \lambda_3^0(R) \end{pmatrix} \quad (4)$$

and the mixing coefficients are  $x$  and  $y$ . This model matches our fit ansatz reasonably well, allowing us to extract values for the mixing parameters, the *magnitudes* of which are plotted in

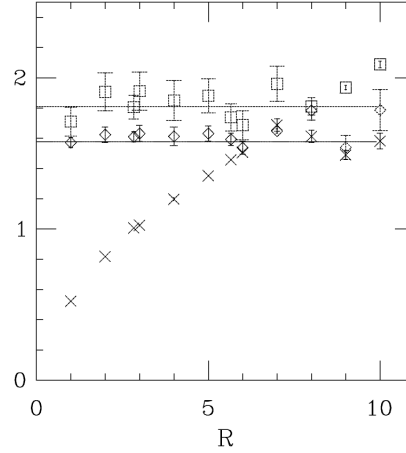


Figure 4. Heavy quark potential and first two excited states  $vs$  separation  $R$ . The dashed and solid lines give the asymptotic values  $2aE_S$  and  $E_P + E_S$ . Jackknife errors are shown.

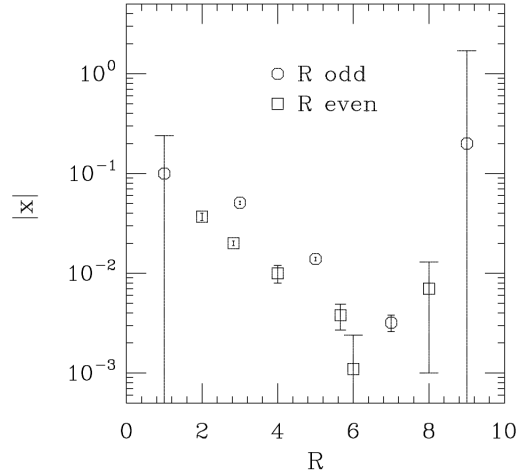


Figure 5. Absolute value of the mixing parameter  $x$   $vs$  separation  $R$ . Odd and even series are distinguished.

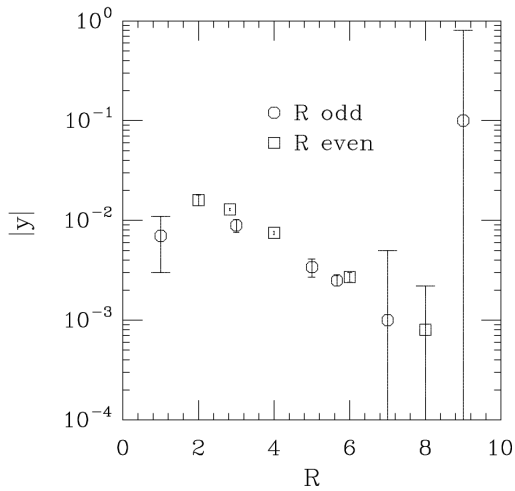


Figure 6. Absolute value of the mixing parameter  $y$  vs separation  $R$ . Odd and even series are distinguished.

Figs. 5 and 6. We see that mixing is weak and is small in the vicinity of level crossing.

#### 4. DISCUSSION

To see string breaking in the heavy-quark potential, it is helpful to introduce explicit meson-meson channels. Mixing among the channels is found to be very weak. String breaking occurs at the first level crossing, *i.e.*, with our quark mass, about one fermi. These results justify a two-channel model of excited quarkonium decay, in which a closed channel populated by bound states couples weakly to an open channel [19].

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