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The charmed-strange meson spectrum from overlap fermions on domain wall dynamical fermion configurations

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The charmed-strange meson spectrum is calculated with overlap valence fermions on 2+1 flavor domain wall dynamical configurations for $32^3 \times 64$ lattices with a spatial size of 2.7 fm. Both the charm and strange quark propagators are calculated with the overlap fermion action. The calculated scalar meson at 2304(22) MeV and axial-vector meson at 2546(27) MeV are in good agreement with the experimental masses of $D^*_{s0}(2317)$ and $D_{s1}(2536)$.

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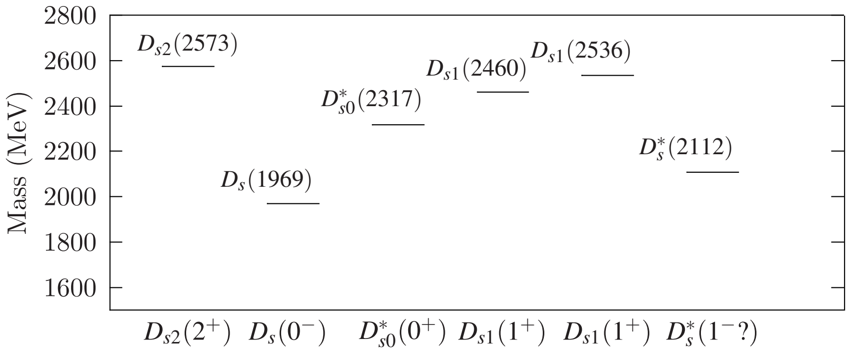
In 2003, BaBar Collaboration announced the discovery of a charmed strange meson $D^*_{s0}(2317)$ [1]. CLEO also reported the observation of this particle in the same year [2]. In the following plot, we show the masses of the charmed strange mesons from the Particle Data Group, in which the newly discovered $D^*_{s0}(2317)$ is a scalar meson and $D_{s1}(2460)$ and $D_{s1}(2536)$ are axial-vector mesons.

Figure 1: The charmed strange meson spectrum from PDG



Predictions of this charmed strange meson spectrum have been made in the quark model [3]. While it gives a good prediction for the tensor, $^3P_1$ axial-vector, pseudoscalar, and vector mesons, its prediction of the $^1P_1$ axial-vector at 2.53 GeV is ~ 70 MeV above the experimental $D_{s1}(2460)$. More puzzling is the prediction of the scalar meson at 2.48 GeV which is ~ 160 MeV above $D^*_{s0}(2317)$. This discrepancy has prompted speculations that $D^*_{s0}(2317)$ is a DK molecule [4], a four quark state [5], or a threshold effect [6] instead of a $c\bar{s}$ meson.

There are also a few lattice calculations. Lattice NRQCD calculation with quenched approximation gives $m(D^*_{s0}) = 2.44(5)$ GeV [7]. The $n_f = 2$ calculation with the heavy quark at the static limit gives $m(D^*_{s0}) = 2.57(11)$ GeV [8]. These are also significantly heavier than the experimental mass of 2.317 GeV. The recent calculation with a relativistic heavy quark (RHQ) action gives $\Delta m = m(D^*_{s0}) - m(D_s) = 0.1243(28)$ GeV, or $m(D^*_{s0}) = 2.093(3)$ GeV [9], which is significantly lower than the experimental mass of D^*_{s0}. The first calculation with overlap valence on 2+1 flavor domain wall fermion configurations was carried out for the charmed-strange mesons [10]. It is found that at the smallest sea mass, the D^*_{s0} is 70(40) MeV higher than the experimental result and the hyperfine splitting is also higher than the experimental one. This is likely due to the $O(m^2a^2)$ error with charm masses as heavy as $am_c = 0.72$ and 0.9 in this study.

Although, in principle, lattice QCD is an ideal tool to calculate the hadron spectrum from first principles, in practice it suffers from systematic errors such as due to discretization effects. These errors can be large for fermion actions which do not have chiral symmetry at finite lattice spacing. In particular, the *ma* errors can be substantial for heavy quarks at the commonly used lattice spacing $a \sim 0.1$ fm.

The overlap fermion action obeys chiral symmetry at finite lattice spacing and is, thus, free of $O(a)$ and $O(ma)$ errors. It is shown that the effective quark propagator of the massive overlap fermion has the same form as that of the continuum[11]; examining the dispersion relations and the hyperfine splittings, it is found that one could use $ma \leq 0.5$ and still keep the $O(m^2a^2)$ errors to

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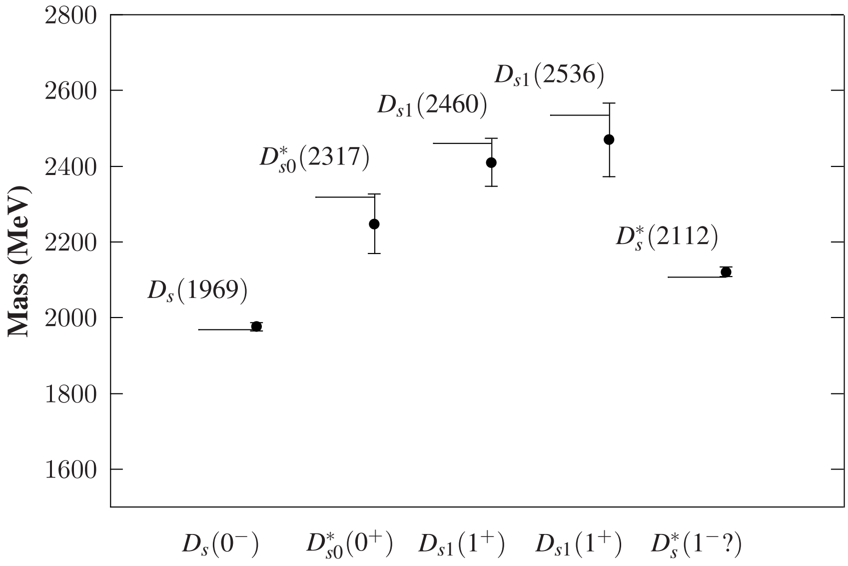
less than 3% to 4% on quenched lattices [12][13]. In the case of the 2+1 flavor dynamical domain-wall fermion configurations with HYP smearing, the range of ma with small deviation from the expected $1/\sqrt{ma}$ behavior for the hyperfine splitting is extended farther than that of the quenched case. With $\rho = 1.5$ for the overlap fermion, we find that the hyperfine splitting for heavy quarks fits well with the form $\frac{a}{\sqrt{ma}} + \frac{b}{\sqrt{ma}^3}$ for the range $0.2 < ma < 0.8$ with deviation as small as 0.4% at $ma = 0.8$ and starting to grow for $ma > 0.8$. In the case of the $32^3 \times 64$ lattice that we work on, the charm mass corresponds to $ma = 0.484$ which is well within the range with negligible m^2a^2 error.

For comparison purposes, we first present our results on charmed strange mesons masses on a quenched $16^3 \times 72$ lattice with Wilson gauge action at $\beta = 6.3345$. With the $r_0 = 0.5$ fm scale, we obtain $a = 0.0560$ fm. The multi-mass overlap inverter is used to calculate propagators for 26 quark masses for ma from 0.02 to 0.85 with the charm mass at $ma = 0.431$ [17][14].

Figure 2: D_S spectrum on quenched $16^3 \times 72$ lattice with overlap fermions.



The quenched results of the scalar and axial D_s, as shown in Fig. 2, are consistent with the experimental masses within error bars; albeit with relatively large errors of ~ 80 MeV. In order to better understand the D_S mesons on the full QCD lattice, it is desirable to use chiral lattice fermions which have smaller $O(m^2a^2)$ errors. We use valence overlap fermions on 2+1 flavor DWF dynamical fermion configurations with HYP smearing. This is a mixed action approach. Since the valence is a chiral fermion, there is only one extra low-energy constant Δ_{mix} in the mixed valence-sea pion masses which needs to be determined in the mixed action partially quenched chiral perturbation theory [15]. The octet pseudoscalar meson masses are thus related to the quark masses as follows:

$$m^2_{v_1,v_2} = B(m_{v_1} + m_{v_2}), \tag{1}$$
$$m^2_{vs} = B(m_v + m_s) + a^2\Delta_{mix} \tag{2}$$
$$m^2_{s_1,s_2} = B(m_{s_1} + m_{s_2}) + a^2\Delta_{sea} \tag{3}$$

$$\Delta_{sea} \sim m_{res} \tag{4}$$

We employ 50 $N_f = 2+1$ domain wall dynamical configurations from RBC and UKQCD collaborations [16]. The lattice has a size $32^3 \times 64$ $L_s = 16$, with a heavier sea quark $m_h a = 0.03$, close to the strange, and light sea quarks $m_l a = 0.006$. The lattice scale is $a^{-1} = 2.42$GeV from $r_0 = 0.47$ fm [16].

For meson correlators, we use standard local interpolating fields. To determine the charm quark mass $m_c a$ we use $m(J/\psi) = 3097$ MeV as the input. It gives $m_c a = 0.484$. Fig. 3 shows the meson spectrum as a function of the quark mass.

Figure 3: The equal quark mass meson spectrum on $32^3 \times 64$ lattice with $m_{sea}a = 0.006$.

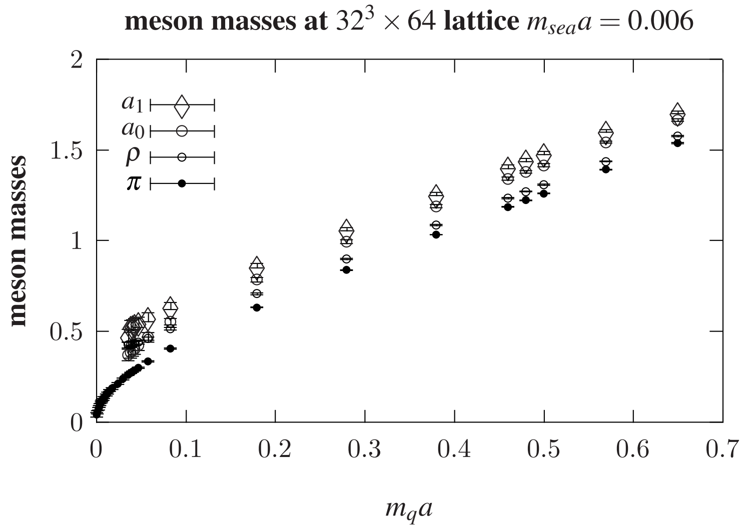


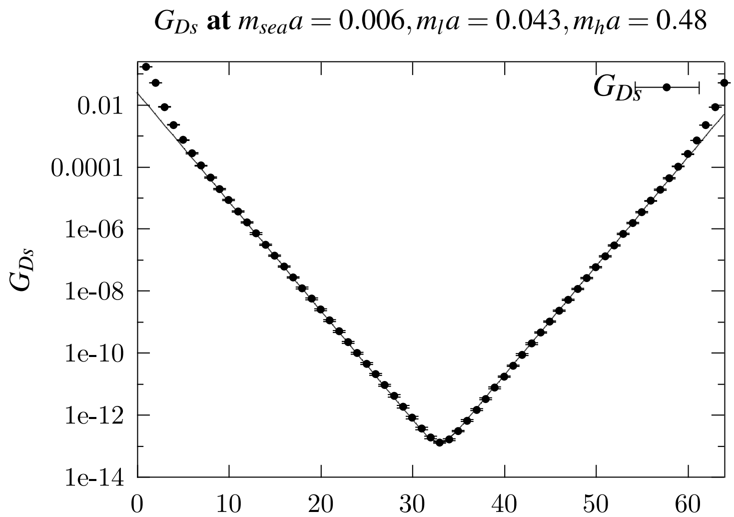
Table 1: Charmonium meson masses

Lattice	J/ψ(MeV)	1^+(MeV)	0^-(MeV)	0^+(MeV)
$32^3 \times 64$ $m_l a = 0.006$	3097	3510(11)	2983(4)	3402(8)
$16^3 \times 72$ quenched	3097	3390(50)	3017(4)	3360(50)
Experiment	3097	3511	2980	3410

In view of the fact that the dynamical fermion calculation is based on a much larger lattice ($32^3 \times 64$ with a spatial size of 2.7 fm) than that of the quenched lattice ($16^3 \times 72$ with a spatial size of 0.9 fm), we expect the present results to have better statistics than the quenched results for both the charmonium [17] and the charmed strange mesons[14] spectra. Indeed as we see in Table 1, the $32^3 \times 64$ dynamical lattice results are much better than those of the quenched results not only in statistics, but also in agreement with experiments. Even the hyperfine splitting agrees with experiment within one sigma.

To calculate the D_s spectrum, we use the same overlap fermion action for both light quark ($m_q a \sim 0.04$) and heavy quark ($m_q a \sim 0.484$). These heavy-light quark propagators are used to construct the charmed-strange meson correlators. The meson correlators of the heavy-light quarks are very well behaved as Fig.4 shows, for example.

Figure 4: Unequal quark mass meson correlator on $32^3 \times 64$ lattice



To determine the charmed strange meson mass we follow these steps:

1. We use standard non-linear fitting of the pseudoscalar meson correlators for different m_s and m_c. The D_S mass results are given in Table 2. For each fixed $m_s a$, the meson mass is a function of $m_c a$, as shown in Fig.5 (left).

2. Then for each $m_s a$, we interpolate data to $m_c a = 0.484$ which was obtained previously from the $m(J/\psi)$ input. Then the data are a function of $m_s a$ only, as shown in Fig. 5 (right).

3. By inputting $m_{D_s} = 1969$ MeV, which corresponds to $m_{D_s} a = 0.8136$, we obtain the strange quark mass $m_s a = 0.0426$.

4. The charmed strange meson masses with other quantum numbers are interpolated to $m_c a = 0.484$ and $m_s a = 0.0426$ to obtain the D_s spectrum. They are compared with experimental data in Table 3 and Fig. 6.

Table 2: The light-heavy quark D_S meson mass matrix

$m_q a$	0.46	0.48	0.50
0.039	0.7873(28)	0.8047(28)	0.8282(29)
0.041	0.7893(27)	0.8067(28)	0.8294(28)
0.043	0.7912(27)	0.8086(27)	0.8302(28)
0.047	0.7917(26)	0.8145(28)	0.8334(27)

Figure 5: The D_S masses for several $m_c a$ with fixed $m_s a$, and for several $m_s a$ after fixing $m_c a$ to 0.484

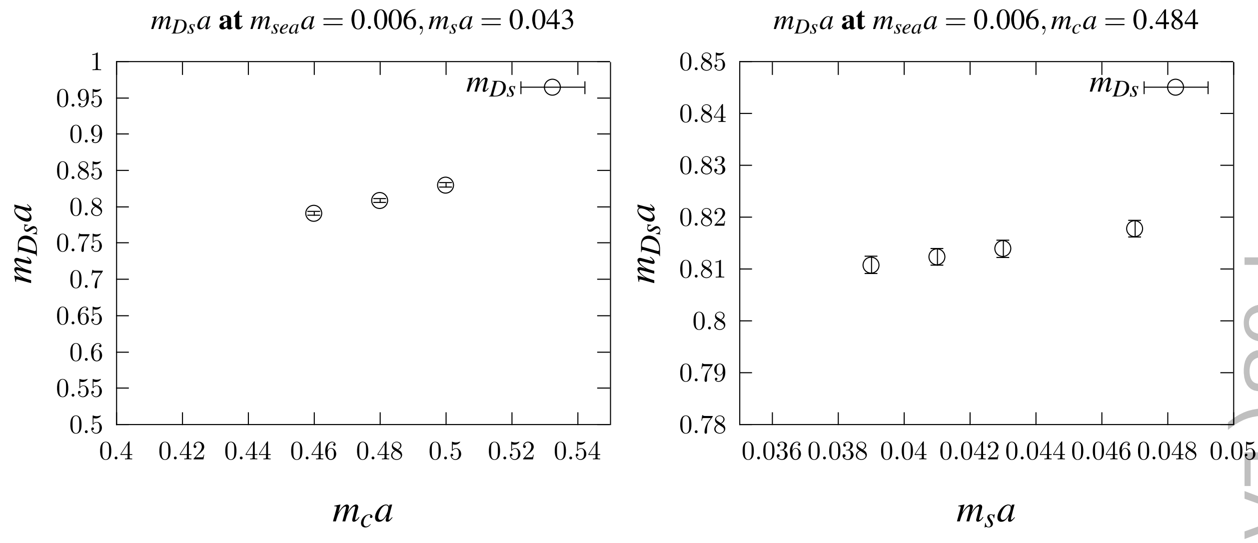


Table 3: Charmed strange meson masses

Lattice	$D_s(0^-)$(MeV)	$D_s^*(1^-)$(MeV)	$D_{s0}^*(0^+)$(MeV)	$D_{s1}(1^+)$(MeV)
$32^3 \times 64(m_{sea}a = 0.006)$	1969	2121(9)	2304(22)	2546(27)
$16^3 \times 72$ (quenched)	1976(11)	2131(13)	2248(78)	2476(92)
Experiment	1968.49(34)	2112.3(5)	2317.8(6)	2535.35(84)

This calculation is preliminary in that we have obtained results for one set of sea quark masses and one lattice spacing. We need to carry out calculation with other sets of sea quark masses to do chiral extrapolation and on a coarser $24^3 \times 64$ lattice in order to extrapolate to the continuum limit. Nevertheless, the preliminary results show that the overlap fermion on 2+1 flavor domain wall dynamical fermion configurations works reasonably well for the D_S spectrum. The results are consistent with experimental masses, especially for $D_{s0}^*(2317)$, the scalar meson. We don't see evidence that $D_{s0}^*(2317)$ is an exotic meson. Rather, it fits well as a scalar $c\bar{s}$ meson.

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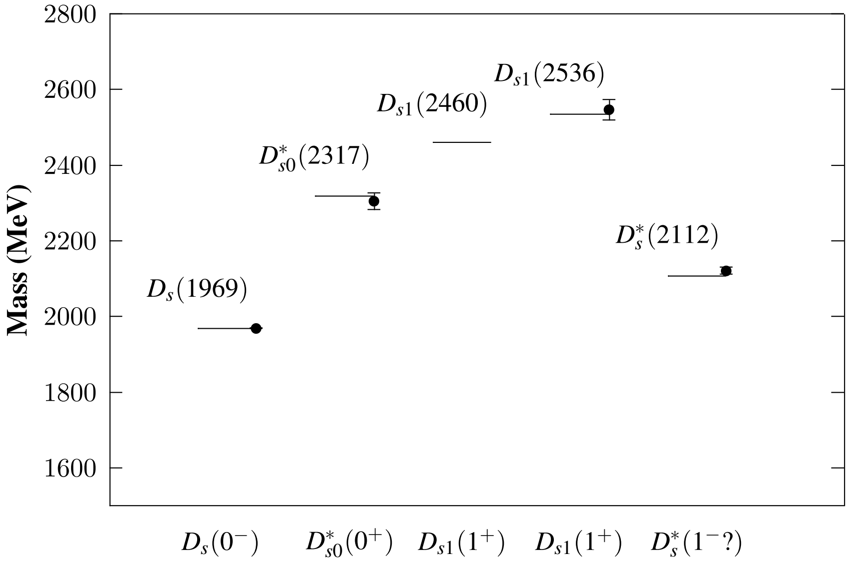
Figure 6: Charmed Strange meson spectrum on $32^3 \times 64$ $m_{sea}a = 0.006$, DWF lattices with overlap valence fermions



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