

Charmed Strange Mesons from Lattice QCD with Overlap Fermions

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The charmed-strange meson masses are calculated on a quenched lattice QCD. The charm and strange quark propagators are calculated on the same lattice with the overlap fermion. $16^3 \times 72$ lattices with Wilson gauge action at $\beta = 6.3345$ are used. The charm and strange quark masses are determined by fitting the J/ψ and ϕ masses respectively. The charmed strange meson spectrum for the scalar, axial, pseudoscalar and vector channels are calculated. They agree with experiments. In particular, we find the scalar meson mass to be 2248(78) MeV which is in agreement with that of D_{s0}^* (2317).

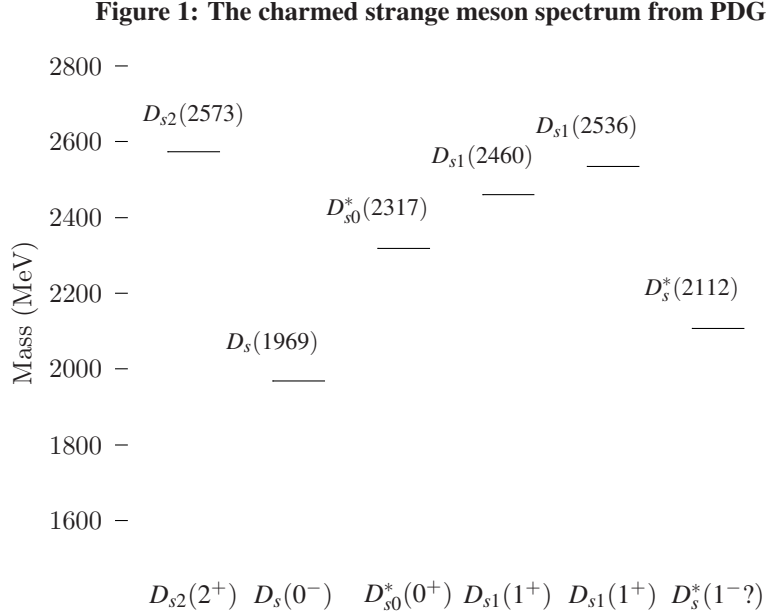
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In 2003, BaBar Collaboration announced the discovery of a charmed strange meson $D_{s0}^*(2317)$ [1]. CLEO also reported the observation of this particle in the same year [2]. In the following plot, we show the masses of the charmed strange mesons 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.



Predictions of these charmed strange meson spectrum have been made in the quark model [3]. While they gave good prediction for the tensor and 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 the speculations that $D_{s0}^*(2317)$ is a DK molecule [4] or 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 $m(D_{s0}^*) = 2.44(5)\text{GeV}$ [8]. The $n_f = 2$ calculation with the heavy quark at the static limit gives $m(D_{s0}^*) = 2.57(11)\text{GeV}$ [9]. These are also significantly heavier than the experimental mass of 2.317 GeV. The recent calculation with a relativistic heavy quark (RHQ) action gives $\Delta m = m(D_{s0}^*) - m(D_s) = 0.1243(28)\text{GeV}$, or $m(D_{s0}^*) = 2.093(3)\text{GeV}$ [10], which is significantly lower than the experimental mass of D_{s0}^* .

Although, in principle, lattice QCD is an ideal tool to calculate hadron spectrum from the first principle, 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 with 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], i.e.

$$D_{ov}(m) = D_{ov} + ma(1 - \frac{1}{2}D_{ov}) \quad (1)$$

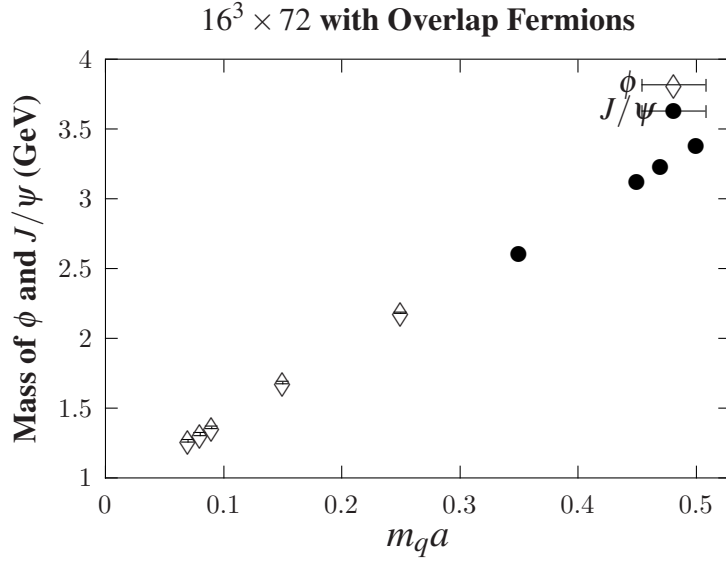
$$S_{eff} = \frac{1 - \frac{1}{2}D_{ov}}{D_{ov}(m)} = \frac{1}{D_c + m}, \quad (2)$$

where $D_c = \frac{D_{ov}}{1 - \frac{1}{2}D_{ov}}$ and $\{D_c, \gamma_5\} = 0$.

As it can be seen from Eq. (1), the formalism is the same for all quark masses. As such, it can be used for both light and heavy quarks as long as the $O(m^2a^2)$ errors are negligible [11]. In fact, the $O(a^2)$ error is also small [12]. By examining the dispersion relations and the hyperfine splittings, it is found that one could use $ma \leq 0.5$ and still keeps the $O(m^2a^2)$ errors to less than 3% to 4% [13].

We carried out a study of charmonium on a quenched $16^3 \times 72$ lattice with Wilson gauge action at $\beta = 6.3345$. With the $r_0 = 0.5\text{fm}$ scale we obtain $a = 0.0560\text{fm}$. Multi-mass overlap inverter is used to calculate propagators for 26 quark masses for ma from 0.02 to 0.85 [14].

Figure 2: Quark masses used to calculate J/ψ and ϕ masses on the 16×72 lattice.



Matching the J/ψ mass $m(J/\psi) = 3.097\text{GeV}$, we obtain the charm quark mass in lattice unit to be $m_c a = 0.431(1)$. Inputting the $\phi(1^-)$ particle mass $m(\phi) = 1.020\text{GeV}$, we obtain the strange quark mass in lattice unit to be $m_s a = 0.0205(32)$. The vector meson mass for a range of quark masses is shown in Fig. 2. We find that the charm and strange quark masses are in the range $0.01 \leq m_q a \leq 0.5$. Thus the $O(m^2 a^2)$ error is expected to be around 1% for the masses of the charmed strange mesons..

We construct the charmed strange meson correlators with the standard local interpolating fields:

$$0^- \implies \chi(x) = \bar{\psi}(x) \gamma_5 \psi(x) \quad (3)$$

$$0^+ \implies \chi(x) = \bar{\psi}(x) \psi(x) \quad (4)$$

$$1^- \implies \chi(x) = \bar{\psi}(x) \gamma_j \psi(x) \quad j = 1, 2, 3 \quad (5)$$

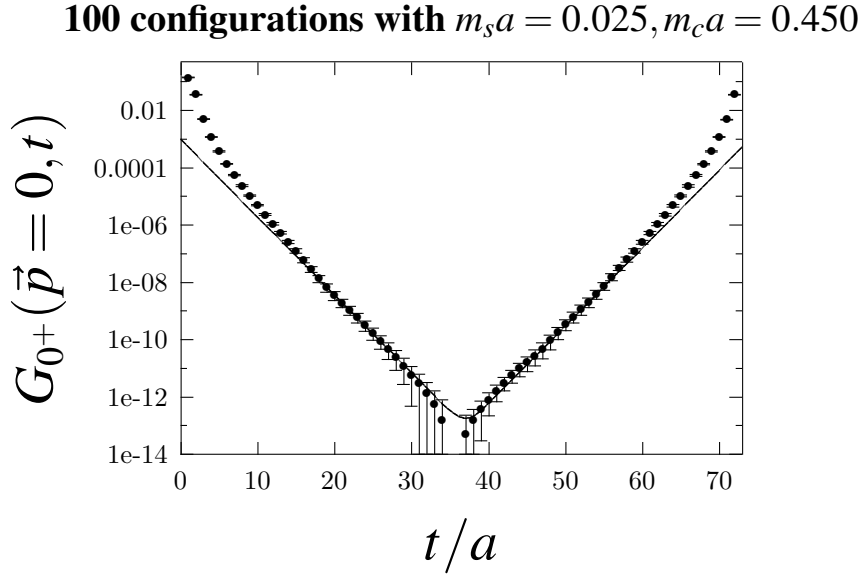
$$1^+ \implies \chi_a(x) = \bar{\psi}(x) \gamma_5 \gamma_j \psi(x) \quad j = 1, 2, 3 \quad (6)$$

$$1^+ \implies \chi_b(x) = \bar{\psi}(x) \gamma_i \gamma_j \psi(x) \quad \{ij\} = \{12\}, \{23\}, \{31\} \quad (7)$$

We do not consider the mixing between χ_a and χ_b for the axial-vector mesons in this work.

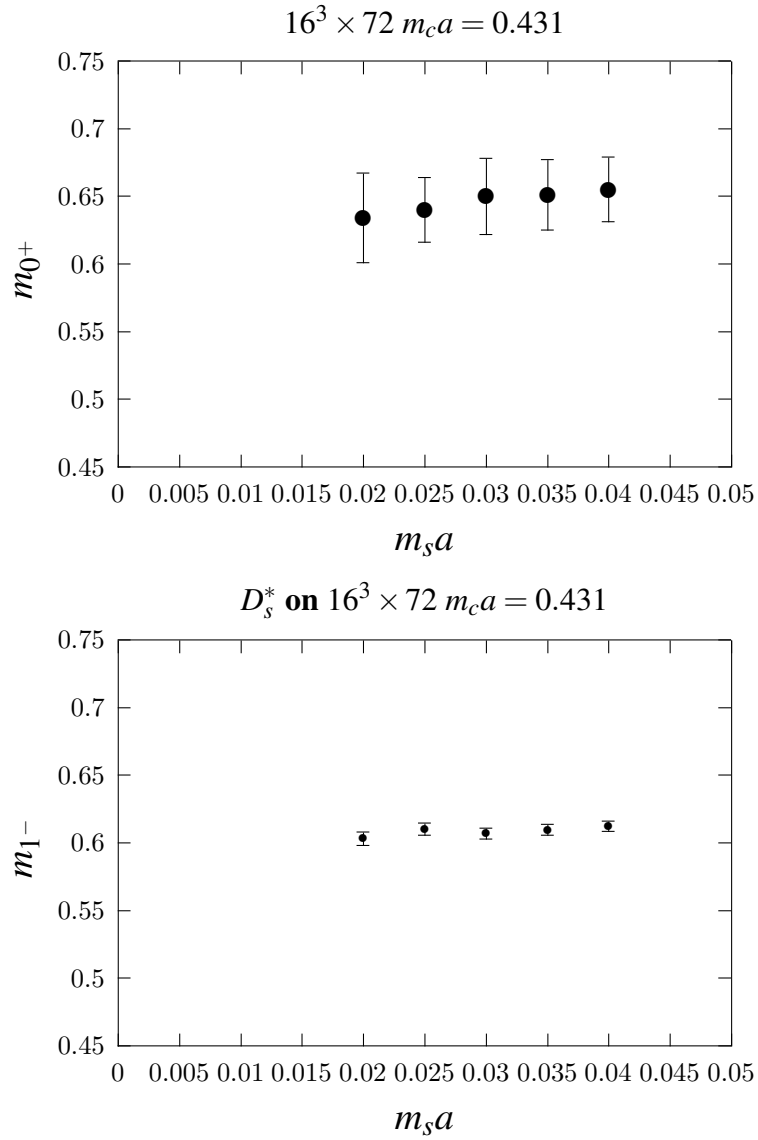
All the meson correlators with 100 configurations show reasonably nice cosh behavior, such as in the scalar channel in Fig. 3.

Figure 3: The charmed strange meson correlator in the scalar channel.



We used 5 quark masses each around those of the charm and strange to construct 25 correlators for the above interpolating fields. We first fix the light quark mass and vary the heavy quark masses to fit the meson masses which correspond to the charm mass at $m_c a = 0.431$. The results for the scalar and vector mesons are plotted against the light quark mass in Fig.4.

We then fix the heavy quark at the charm mass and fit the light quark masses which correspond to the strange mass at $m_s a = 0.0205$. This way, we obtained the charmed strange meson masses for

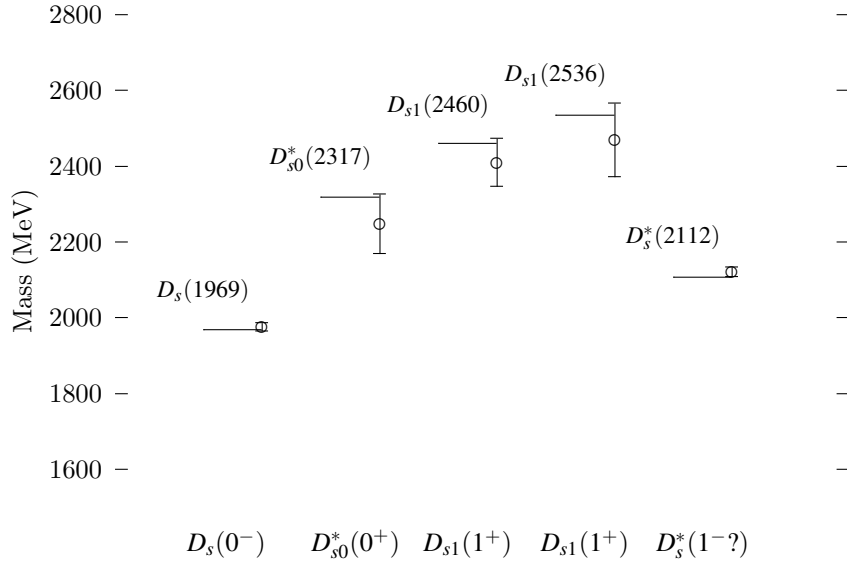
Figure 4: The charmed scalar and vector meson mass varying with light quark mass

each of the meson interpolation field. The numerical results are shown in Table 1. The experimental data are from the PDG particle listings.

Our lattice results are plotted in Fig. 5 together with the experimental data.

Table 1: charmed strange meson masses

Particle	Mass($\times a$)	Lattice (MeV)	Exp. (MeV)
$D_s(0^-)$	0.5608(31)	1976(11)	1968.49(34)
$D_s^*(1^-)$	0.6049(36)	2131(13)	2112.3(5)
$D_{s0}^*(0^+)$	0.638(22)	2248(78)	2317.8(6)
$D_{s1}(1_a^+)$	0.684(18)	2410(63)	2459.6(6)
$D_{s1}(1_b^+)$	0.703(26)	2476(92)	2535.35(84)

Figure 5: Calculated charmed strange meson spectrum in comparison with the experimental results

We see that the pseudoscalar (D_s) and the vector (D_s^*) agree with the experimental results very well, assuming the D_s^* at 2112 MeV is the 1^- meson. All the p-waves states (0^+ and the two 1^+) agree with the experiments within one sigma. In particular, we find the 0^+ meson with the $\bar{\psi}\psi$ interpolation field at 2248(78) MeV to be much higher than the quark model prediction. This suggests that $D_{s0}^*(2317)$ may well be the conventional $c\bar{s}$ meson.

To have a better estimate of the D_{s0}^* mass, we used the ratio method to calculate the mass difference. Since the correlators are calculated from the same gauge configurations, the ratio method is expected to reduce fluctuations. We calculated the ratio between the scalar and pseudoscalar correlators.

$$\frac{G(0^+)}{G(0^-)} \sim \exp(-\Delta m \cdot t), \quad \Delta m = m(0^+) - m(0^-). \quad (8)$$

The preliminary result is $\Delta m = m(D_{s0}^*) - m(D_s) = 275(53)$ MeV which is about a sigma from the experimental result of 349.3(7) MeV.

To summarize, we have carried out a calculation of the charmed strange meson masses with the overlap fermion on quenched $16^3 \times 72$ lattices. The calculated masses are consistent with the

experimental results within error bars. The $J^P = 1^-$ meson mass matches with $D_s^*(?)(2112)$ very well. This implies that $D_s^*(?)(2112)$ is indeed the expected vector meson. The scalar meson mass at 2248(78) MeV is higher than the prediction of the quark model and is in agreement with the experimental mass of $D_{s0}^*(2317)$.

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