Excited Spectroscopy of Mesons Containing Charm Quarks From Lattice QCD

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(For the Hadron Spectrum Collaboration)
Outline

1. Experimental motivation
2. Ensemble details
3. HadSpec recipe for spectroscopy
4. Results
   - Charmonium spectrum
   - $D$ and $D_s$ spectra
   - Hybrid mesons
   - $D\pi$ scattering ($I = 3/2$) - Preliminary
Pre 2003 - charm spectroscopy well explained via quark models - $^{2S+1}L_J$

New narrow charmonium-like structures are observed by BABAR and Belle above the open charm threshold ("X,Y,Z's")

Too many states for the $^{2S+1}L_J$ pattern to explain $\Rightarrow$ renewed theoretical interest . . . what could the states be?

- $X(3872)$: close to the $D\bar{D}^*$ threshold $\Rightarrow$ a molecular meson?
- $X(4260)$: a $1^{--}$ hybrid meson?
- $X(4430)^\pm$: a charged entity $\Rightarrow$ can’t be $c\bar{c}$, maybe a tetra-quark?

Still no clear picture has emerged
BABAR observes the $D_{s0}^*(2317)^\pm$ state

[B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 90 (2003) 242001]

CLEO confirms the BABAR discovery and observes a further resonance $D_{s1}(2460)^\pm$

[D. Besson et al. [CLEO Collaboration], Phys. Rev. D 68 (2003) 032002]

Significantly Lighter and narrower than quark model predictions

[Observed

Predicted

]

Mass (MeV)

1800

2000

2200

2400

2600

2600

2600

[Observed

Predicted

]

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Calculations performed on lattices generated by the **Hadron Spectrum Collaboration**

- **Dynamical** - $N_f = 2 + 1$
- **Anisotropic** - $\xi = a_s/a_t \sim 3.5$
- **Scale set via** $M_\Omega$: $a_s = 0.1227(8)$ fm, $a_t^{-1} = 5.67(4)$ GeV
- **Two volumes**: $16^3 \times 128$ and $24^3 \times 128$
- **Clover fermions**: On-shell $O(a)$ improvement
- **Spatial links** are **stout smeared**
- **Quark fields** are **distilled**
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**Caveat:** Pion mass $\sim 391$ MeV
Recipe for the calculation of **extensive** spectra:

1. Use basis of local and non-local operators from distilled fields

   \[ \bar{\Psi}(x) \Gamma D_i D_j \ldots \Psi(x) \]

   We include:
   - All combinations of \( \gamma \)-matrices and derivatives up to three derivatives
   - Operators \( \sim F_{\mu \nu} \Rightarrow \) access gluonic degrees of freedom
   - Operators that let us explore all \( J^P(C) \) up to \( J = 4 \)

2. Build a **correlation matrix** from two-point correlation functions

   \[ C_{ij} = \langle 0 | O_i O_j^\dagger | 0 \rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E_n} e^{-E_n t} \]
Use a variational method - solve the generalised eigenvalue equation

\[ C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)} \]

This gives:

- **Eigenvalues**: \( \lambda^{(n)}(t) \sim e^{-E_nt} \left[ 1 + O(e^{-\Delta Et}) \right] \) - principle correlator

- **Eigenvectors**: Relate to overlaps \( Z_i^{(n)} = \sqrt{2E_ne^{E_nt_0}/2} v_j^{(n)\dagger} C_{ji}(t_0) \)

Use overlaps to assign each extracted state a continuum spin

- Operators of definite \( J^{PC} \) were constructed in step 1 and subduced into the relevant irrep

- A subduced operator carries a memory of the continuum spin \( J \), from which it was subduced - it overlaps predominantly with states of this \( J \)
Results - Hidden Charm Sector
Charmonium Spectrum - By $J^{PC}$

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Large overlap with operators $\mathcal{O} \sim F_{\mu\nu}$

Lightest hybrid supermultiplet: 
(c$\bar{c}$ in S-wave) $\otimes (J_g^{PC} = 1^{+-}) \Rightarrow [(0, 1, 2)^{-+}, 1^{--}]$

Excited hybrid supermultiplet: (c$\bar{c}$ in P-wave) $\otimes (J_g^{PC} = 1^{+-}) \Rightarrow [0^{+-}, (1^{+-})^3, (2^{+-})^2, 3^{+-}, (0, 1, 2)^{++}]$
Results - Open Charm Sector
D Meson Spectrum - By $J^P$

**Lattice Experiment**

- **G - Wave**
- **D - Wave**
- **S - Wave**
- **D - Wave**
- **S - Wave**
- **P - Wave**
- **F - Wave**

$D\pi$

$D_{s\bar{K}}$

$D_{s\bar{K}}$

$D\pi$

$D\pi$
- Large overlap with operators $\mathcal{O} \sim F_{\mu\nu}$

- Lightest hybrid supermultiplet - same pattern and scale as in Charmonium and Light meson sectors [J. Dudek, arXiv:1106.5515]
Results - $D\pi$ Scattering
$D\pi$ Scattering Phase Shift for $l = 0$ - Preliminary

**Graph:**

- **Horizontal Axis:** $a_t E_{cm}$
- **Vertical Axis:** $\delta_0$(deg)

**Data Points:**
- $P = (0,0,0)$
- $P = (1,0,0)$
- $P = (1,1,0)$
- $P = (1,1,1)$

**Legend:**

- Red markers with error bars

**Note:**
- PRELIMINARY

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Conclusions

- Computed charmonium spectrum - observe exotic states
- Computed $D$ and $D_s$ spectra - multi-hadron effects may be important to understand the $D_{s0}^*(2317)^\pm$ and $D_{s1}(2460)^\pm$ states
- Spectra generally well explained by quark model
- Observe extra hybrid states
- Early stages of $D\pi$ Scattering ($I = 3/2$)