Charm Spectroscopy From Lattice QCD

Graham Moir

University of Cambridge

Electromagnetic Interactions with Nucleons and Nuclei
Paphos, 4th November 2015
Outline

1. Spectroscopy on the Lattice
2. Low-Lying Precision spectroscopy
3. Excited Hidden and Open-Charm Spectra
4. Hybrid Mesons
5. Searches for $X$, $Y$, $Z$'s
6. Charmed Scattering
The Charm Sector

- Simple Quark Model $\Rightarrow 2S+1 L_J$
- Fits low-lying open and hidden-charm spectra well

Narrow charmonium-like ‘X,Y,Z’ states:
- Tetraquarks?
- Hybrid mesons?
- Hadro-charmonium?
- Molecules?

In principle, lattice field theory can determine the \textit{entire} spectrum of QCD including \textit{exotic} manifestations

- Spectroscopic information is obtained via

\[ C(t) = \langle 0 | \mathcal{O}(t) \mathcal{O}^\dagger(0) | 0 \rangle = Ae^{-E_0t} + Be^{-E_1t} + \cdots \]
In principle, lattice field theory can determine the entire spectrum of QCD including exotic manifestations.

- Spectroscopic information is obtained via
  \[ C(t) = \langle 0 | \mathcal{O}(t) \mathcal{O}^\dagger(0) | 0 \rangle = A e^{-E_0 t} + B e^{-E_1 t} + \cdots \]

- The simplest operators are local fermion bilinears
  \[ \bar{\Psi}(x) \Gamma \Psi(x) \]

Symmetries of operators dictate which states can be determined:

- \( \Gamma = \gamma_5 \Rightarrow J^P = 0^- \)
- \( \Gamma = \gamma_i \Rightarrow J^P = 1^- \)
- \( \Gamma = \{1, \gamma_0, \gamma_5, \gamma_0 \gamma_5, \gamma_i, \gamma_0 \gamma_i, \gamma_5 \gamma_i, [\gamma_i, \gamma_j] \} \)
Systematics under control:

- $N_f = 2 + 1 + 1$
- Large Volume
- Continuum extrapolation
- Chiral extrapolation
- Neglects charm annihilation (OZI rule)

- Splittings (which are known to be sensitive to finite cut-off) are determined accurately
- Similar accuracy in the open-charm sector
The Hadron Spectrum Collaboration have computed extensive hidden and open-charm spectra by including:

- A large basis of local and non-local operators ⇒ access to different radial and orbital structures
- Operators that explore all $J \leq 4$
- Operators $\sim F_{ij}$ ⇒ access gluonic degrees of freedom
The **Hadron Spectrum Collaboration** have computed extensive hidden and open-charm spectra by including:

- A large basis of local and non-local operators ⇒ access to different radial and orbital structures
- Operators that explore all $J \leq 4$
- Operators $\sim F_{ij}$ ⇒ access gluonic degrees of freedom

Solving a GEVP gives information on ground and excited states:

- **Masses** are given by the eigenvalues
- **Spins** can be identified using the eigenvectors
The Hadron Spectrum Collaboration have computed extensive hidden and open-charm spectra by including:

- A large basis of local and non-local operators ⇒ access to different radial and orbital structures
- Operators that explore all $J \leq 4$
- Operators $\sim F_{ij}$ ⇒ access gluonic degrees of freedom

Solving a GEVP gives information on ground and excited states:

- Masses are given by the eigenvalues
- Spins can be identified using the eigenvectors

Caveats:
- Light quarks are heavy: $M_\pi = 391\,\text{MeV}$
- One lattice spacing ⇒ no control over cut-off effects
- Assumes all states are stable
$D_s$ Meson Spectrum

Graham Moir

Charm Spectroscopy From Lattice QCD

4th November 2015 6 / 18
- Large overlap with operators $\mathcal{O} \sim [D_i, D_j] \sim F_{ij}$

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

- Large overlap with operators $\mathcal{O} \sim [D_i, D_j] \sim F_{ij}$

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

- **Excited hybrid supermultiplet:**
  
  \((c\bar{c} \text{ in } P\text{-wave}) \otimes (J_g^{PC} = 1^{+-}) \Rightarrow [0^{+-}, (1^{+-})^3, (2^{+-})^2, 3^{+-}, (0, 1, 2)^{++}]\)
Potential non-relativistic QCD $\Rightarrow$ static quark approximation with glue degrees of freedom

- A consistent picture emerges across the charm sector (and the light sector - c.f. Dave Wilson's talk)
Idea: “See if extra energy level appears when appropriate operator is included”
**Idea:** “See if extra energy level appears when appropriate operator is included”

- Search in the $J^{PC} = 1^{++} (I = 0)$ channel
- Several $c\bar{c}$ and $DD^*$ operators included

Candidate for **bound $X(3872)$** 13(6) MeV below $DD^*$ threshold

- $M_\pi = 310$ MeV $\Rightarrow$ affects position of $DD^*$ threshold
- Further evidence for bound $X(3872)$ in [arXiv:1307.5172] via $D\bar{D}^*$ scattering
Towards the $X(3872)$ - A Step Closer

Previous study of $D\bar{D}^*$ scattering - pole just below $DD^*$ threshold. Further investigation...
Previous study of $D\bar{D}^*$ scattering - pole just below $DD^*$ threshold. Further investigation...

- Operators: $c\bar{c}$, $c\bar{c}(u\bar{u} + d\bar{d})$, $D(0)\bar{D}^*(0)$, $D(1)\bar{D}^*(-1)$, $J/\psi\omega$, . . .

- Four-quark operator has negligible effect on spectrum

- $D(0)\bar{D}^*(0)$ and $c\bar{c}$ Fock components important for $X(3872)$

- Many caveats!
Search for the $Y(4140)$ and the $Y(4274)$

Search in the $J^{PC} = 1^{++}$ ($I = 0$) channel with hidden (valence) strangeness.
Search in the $J^{PC} = 1^{++} (I = 0)$ channel with hidden (valence) strangeness.

- Operators: $c\bar{c}, c\bar{c}s\bar{s}, D_s(p)\bar{D}_s^*(-p), J/\psi(p)\phi(-p), \ldots$

- Observe levels identified as $\chi_{c1}$, the $X(3872)$ and scattering two-meson states

- Observe no extra energy levels

- Only a first exploration with many caveats $\Rightarrow$ does not rule out this channel!
Search in the $J^{PC} = 1^{++} (l = 1)$ channel.
Search in the $J^{PC} = 1^{++}$ ($I = 1$) channel.

- Operators: $c\bar{c}ud$, $D(p)\bar{D}^*(-p)$, $J/\psi(p)\rho(-p)$, $\chi_{c0}(p)\pi(-p)$, ...

- Four-quark operator has negligible effect on spectrum

- No evidence for an $I = 1$ partner of the $X(3872)$

- No extra states corresponding to the $Z_c^+(4050)$ or the $Z_c^+(4250)$

- Many caveats $\Rightarrow$ channel not ruled out!
Wick rotation $\Rightarrow$ loss of scattering information

But

Lüsher formalism $\Rightarrow$ phase shifts and widths obtained by finiteness of volume

$$\det \left[ \delta_{ij}\delta_{ll'}\delta_{nn'} + \nu p_i t^{(l)}_{ij} \left( \delta_{ll'}\delta_{nn'} + \nu M_{ln;l'n'}(q_i)^2 \right) \right] = 0$$

- $i, j$ label channel (e.g. $D\pi, D\eta$) $\Rightarrow$ can perform a coupled channel analysis (c.f. Dave Wilson’s Talk)
- $t^{(l)}_{ij}$ is infinite volume scattering t-matrix
- $M_{ln;l'n'}(q_i)^2$ - effect of finite volume
- $\Lambda$ $\Rightarrow$ Partial waves mix
A More Rigorous Approach - Scattering on the Lattice

Wick rotation ⇒ loss of scattering information

But

Lüscher formalism ⇒ phase shifts and widths obtained by finiteness of volume

\[
\det \left[ \delta_{ij} \delta_{ll'} \delta_{nn'} + \nu p_i t_{ij}^{(1)} \left( \delta_{ll'} \delta_{nn'} + \nu M_{ln;l'n'}(q_i) \right) \right] = 0
\]

- \(i, j\) label channel (e.g. \(D\pi, D\eta\)) ⇒ can perform a coupled channel analysis (c.f. Dave Wilson’s Talk)
- \(t_{ij}^{(1)}\) is infinite volume scattering t-matrix
- \(M_{ln;l'n'}(q_i)^2\) - effect of finite volume
- \(\Lambda\) ⇒ Partial waves mix

“Compute multi-particle spectra and feed into formula”
$D\pi$ \quad (l = 3/2)
Scattering in the Charm Sector (Preliminary)

$D_\pi \ (I = 3/2)$ S-Wave Phase Shift

\[ D \pi \ (I = 3/2) \] S-Wave Phase Shift

\[ \alpha_t E_{cm} \]

\[ \delta_0 / ^\circ \]

$P = (0,0,0)$

$P = (0,0,1)$

$P = (0,1,1)$

$P = (1,1,1)$

$D \pi \pi$

$D^* \rho$
Conclusions and Outlook

Conclusions:

1. Precision calculations of low-lying spectra - almost no systematics!

2. Extensive calculations of excited open and hidden-charm spectra
   - Approximates all states as stable
   - Generally well explained by simple $q\bar{q}$ picture
   - Observed hybrid super-multiplet structure - consistent across light and charm sectors

3. First hints toward the $X(3872)$

Outlook:

1. Searches for other exotics ongoing

2. Detailed coupled channel analysis of $D\pi$ (and others) scattering ongoing

3. Scattering of $D\bar{D}^*$ and other interesting channels to come soon