Highly excited and exotic meson spectroscopy from lattice QCD

Christopher Thomas, Jefferson Lab

thomasc@jlab.org

Confinement IX, Madrid, August 2010

With Jo Dudek, Robert Edwards, Mike Peardon,
David Richards and the *Hadron Spectrum Collaboration*

Outline

- Introduction and motivation
- Method outline - excited spectra from LQCD
- Results – isovector and kaon spectra
- Summary and outlook

PRL 103 262001 (2009)
PR D82 034508 (2010)

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

Exotics ($J^{PC} = \mathbf{1}^{-+}, \mathbf{2}^{+-}, \dots$)? – can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

Exotics ($J^{PC} = 1^{-+}, 2^{+-}, \dots$)? — can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Two spin-half fermions: $2S+1L_J$

Parity: $P = (-1)^{(L+1)}$

Charge Conj Sym: $C = (-1)^{(L+S)}$

$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}, 1^{+-}, 2^{--}, 2^{++}, 2^{-+}, \dots$

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

Exotics ($J^{PC} = 1^{-+}, 2^{+-}, \dots$)? — can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Photoproduction at GlueX (JLab 12 GeV upgrade)

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

Exotics ($J^{PC} = 1^{-+}, 2^{+-}, \dots$)? — can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Photoproduction at GlueX (JLab 12 GeV upgrade)

Use Lattice QCD to extract excited spectrum...

... and photocouplings (tested in charmonium)

PR D77 034501 (2008), PR D79 094504 (2009)

Spectroscopy on the lattice

Calculate **energies** and **matrix elements** (“overlaps”, Z’s)
from correlation functions of meson interpolating fields

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Spectroscopy on the lattice

Calculate **energies** and **matrix elements** (“overlaps”, Z’s)
from correlation functions of meson interpolating fields

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Construct operators which
only overlap on to one spin
in the continuum limit

$$O(t) = \sum_{\vec{x}} e^{i\vec{p} \cdot \vec{x}} \bar{\psi}(x) \Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \dots \psi(x)$$

‘Distillation’ technology for constructing
on lattice PR D80 054506 (2009)

(p = 0)

definite J^{PC}

Spectroscopy on the lattice

Calculate **energies** and **matrix elements** (“overlaps”, Z’s)
from correlation functions of meson interpolating fields

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Construct operators which
only overlap on to one spin
in the continuum limit

$$O(t) = \sum_{\vec{x}} e^{i\vec{p} \cdot \vec{x}} \bar{\psi}(x) \Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \dots \psi(x)$$

‘Distillation’ technology for constructing
on lattice PR D80 054506 (2009)

(p = 0)

definite J^{PC}

$$Z_i^{(n)} \equiv \langle 0 | O_i | n \rangle$$

$$C_{ij}(t) = \sum_n \frac{e^{-E_n t}}{2 E_n} \langle 0 | O_i(0) | n \rangle \langle n | O_j(0) | 0 \rangle$$

Variational Method

Large basis of operators $\rightarrow$ matrix of correlators

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Generalised eigenvector problem:

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

Variational Method

Large basis of operators $\rightarrow$ matrix of correlators

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Generalised eigenvector problem:

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

Eigenvalues $\rightarrow$ energies

$$\lambda^{(n)}(t) \rightarrow e^{-E_n(t-t_0)}$$

$$(t \gg t_0)$$

Variational Method

Large basis of operators $\rightarrow$ matrix of correlators

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Generalised eigenvector problem:

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

Eigenvalues $\rightarrow$ energies

$$\lambda^{(n)}(t) \rightarrow e^{-E_n(t-t_0)}$$

$$(t \gg t_0)$$

Eigenvectors $\rightarrow$ optimal linear combination of operators to overlap on to a state

$$\Omega^{(n)} \sim \sum_i v_i^{(n)} O_i$$

$Z^{(n)}$ related to eigenvectors

$$Z_i^{(n)} \equiv \langle 0 | O_i | n \rangle$$

Variational Method

Large basis of operators $\rightarrow$ matrix of correlators

$$C_{ij}(t) = \langle 0 | O_i(t) O_j(0) | 0 \rangle$$

Generalised eigenvector problem:

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

Eigenvalues $\rightarrow$ energies

$$\lambda^{(n)}(t) \rightarrow e^{-E_n(t-t_0)}$$

$$(t \gg t_0)$$

Eigenvectors $\rightarrow$ optimal linear combination of operators to overlap on to a state

$$\Omega^{(n)} \sim \sum_i v_i^{(n)} O_i$$

$Z^{(n)}$ related to eigenvectors

$$Z_i^{(n)} \equiv \langle 0 | O_i | n \rangle$$

Var. method uses orthog of eigenvectors; don't just rely on separating energies

Light Meson Spectroscopy

- Dynamical calculation (unquenched – includes light quark loops)
- Anisotropic – finer in temporal direction ($a_s/a_t = 3.5$, $a_s \sim 0.12$ fm)

Lattice details in: PR D78 054501, PR D79 034502

- Only connected diagrams – isovectors ($I=1$) and kaons

Light Meson Spectroscopy

- Dynamical calculation (unquenched – includes light quark loops)
- Anisotropic – finer in temporal direction ($a_s/a_t = 3.5$, $a_s \sim 0.12$ fm)

Lattice details in: PR D78 054501, PR D79 034502

- Only connected diagrams – isovectors ($I=1$) and kaons
- As an example: three degenerate ‘light’ quarks ($N_f = 3$, $M_\pi \approx 700$ MeV)
- Also ($N_f = 2+1$) $M_\pi \approx 520, 440, 400$ MeV

SU(3) symmetry

Method details and results: PRL 103 262001 (2009), PR D82 034508 (2010)

$N_f = 3$ isovectors

16^3 (~2 fm) and 20^3 (2.4 fm)

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

First $J = 4$ mesons in LQCD

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

First $J = 4$ mesons in LQCD

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

First $J = 4$ mesons in LQCD

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

D + G-waves

First J = 4 mesons in LQCD

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

D + G-waves

First J = 4 mesons in LQCD

$N_f = 3$ isovectors

16^3 (~ 2 fm) and 20^3 (2.4 fm)

Lower pion masses

Lower pion masses

Exotics summary

Exotics summary

Kaons

Lower the light quark mass ($N_f = 2+1$) — SU(3) sym breaking

M_π / MeV	700	520	440	400
M_K / M_π	1	1.2	1.3	1.4

c.f. physical
 $M_K / M_\pi = 3.5$

Kaons

Lower the light quark mass ($N_f = 2+1$) — SU(3) sym breaking

M_π / MeV	700	520	440	400
M_K / M_π	1	1.2	1.3	1.4

c.f. physical
 $M_K / M_\pi = 3.5$

No longer is C-parity a good quantum number for kaons (or a gen. of C-parity)

Combine J^{P+} and J^{P-} operators

Physically, axial kaons [$K_1(1270)$, $K_1(1400)$] are a mixture
Suggested mixing angle $\approx 45^\circ$ (combination of exp and models)

But...

Kaons

Lower th

M_π / M_K

M_K / M_π

No long

Combin

Physical
Suggest

But...

$$C_{ij} / \sqrt{C_{ii} C_{jj}}$$

16^3

$M_\pi \approx 400 \text{ MeV}$

$M_K / M_\pi \approx 1.4$

c.f. physical

$M_K / M_\pi = 3.5$

for a gen. of C-parity)

odels)

Kaons - spectrum

Kaons – Various pion masses

Kaons – Various pion masses

Multi-particle states?

Finite box
 → discrete allowed momenta
 → discrete spectrum of multiparticle states

Multi-particle states?

Finite box
 → discrete allowed momenta
 → discrete spectrum of multiparticle states

Expect two-meson states above $2m_\pi$

$$2m_\pi \sim 0.85 m_\Omega$$

Where are they?

Summary and Outlook

Summary

- Our first results on light mesons – **technology and method work**
- **First spin 4 meson** extracted and confidently identified on lattice
- **Exotics** (and non-exotic **hybrid** candidates)
- Isovectors and kaons

Summary and Outlook

Summary

- Our first results on light mesons – **technology and method work**
- **First spin 4 meson** extracted and confidently identified on lattice
- **Exotics** (and non-exotic **hybrid** candidates)
- Isovectors and kaons

Outlook – ongoing work

- Multi-meson operators – resonance physics
- Disconnected diagrams – isoscalars and multi-mesons
- Baryons
- Photocouplings
- Lighter pion masses and larger volumes

Extra Slides

Kaons – Operator Overlaps (Z's)

16^3

$M_\pi \approx 520 \text{ MeV}$

$M_K/M_\pi \approx 1.2$

16^3

$M_\pi \approx 400 \text{ MeV}$

$M_K/M_\pi \approx 1.4$

Kaons – Operator Overlaps (Z's)

16^3

$M_\pi \approx 520 \text{ MeV}$

$M_K/M_\pi \approx 1.2$

16^3

$M_\pi \approx 400 \text{ MeV}$

$M_K/M_\pi \approx 1.4$

(2)

J^{++}

Kaons – Operator Overlaps (Z's)

16^3

$M_\pi \approx 520 \text{ MeV}$

$M_K/M_\pi \approx 1.2$

16^3

$M_\pi \approx 400 \text{ MeV}$

$M_K/M_\pi \approx 1.4$

J^{++}

J^{+-}

QCD on a Lattice

Discretise on a grid (spacing = a) – regulator

Finite volume $\rightarrow$ finite no. of d.o.f.

QCD on a Lattice

Discretise on a grid (spacing = a) – regulator

Finite volume $\rightarrow$ finite no. of d.o.f.

Quarks fields on lattice sites

$$\psi(x) \rightarrow \psi_x$$

Gauge fields on links

$$A_\mu(x) \rightarrow U_{x,\mu} = e^{-aA_{x,\mu}}$$

QCD on a Lattice

Discretise on a grid (spacing = a) – regulator

Finite volume $\rightarrow$ finite no. of d.o.f.

Quarks fields on lattice sites

$$\psi(x) \rightarrow \psi_x$$

Gauge fields on links

$$A_\mu(x) \rightarrow U_{x,\mu} = e^{-aA_{x,\mu}}$$

Path integral formulation

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U f(\psi, \bar{\psi}, U) e^{iS[\psi, \bar{\psi}, U]}$$

QCD on a Lattice

Discretise on a grid (spacing = a) – regulator

Finite volume $\rightarrow$ finite no. of d.o.f.

Quarks fields on lattice sites

$$\psi(x) \rightarrow \psi_x$$

Gauge fields on links

$$A_\mu(x) \rightarrow U_{x,\mu} = e^{-aA_{x,\mu}}$$

Path integral formulation

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U f(\psi, \bar{\psi}, U) e^{iS[\psi, \bar{\psi}, U]}$$

Euclidean time: $t \rightarrow i\tau$

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U f(\psi, \bar{\psi}, U) e^{-\tilde{S}[\psi, \bar{\psi}, U]}$$

Do fermion integral analytically, then use importance sampling Monte Carlo