Pentaquarks: Lattice overview

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Pentaquarks in Lattice QCD

Indentifying resonances in Lattice QCD

5Q studies to date

Opinions vary

Isoscalar-3/2+: maybe exciting?
Particle Energies in Lattice QCD

Write operator with correct quantum numbers
eg. Nucleon \[ \chi_N = \varepsilon^{abc}[u^T_a(x)C\gamma_5d_b(x)]u_c(x) \]

Measure 2-pt correlation function

\[ \langle \chi(t)\bar{\chi}(0) \rangle = \sum_{n=0}^{\infty} \lambda_n \bar{\lambda}_n \exp(-E_nt) \]

\[ \langle \chi'(t)\bar{\chi}'(0) \rangle = \sum_{n=0}^{\infty} \lambda'_n \bar{\lambda}'_n \exp(-E_nt) \]

Large Euclidean time \[\rightarrow\] Low-lying energy states
“Resonances” in Lattice QCD

- Lowest-lying bound states: *EASY*
- “Unstable” particles: *DIFFICULT*
- M. Lüscher: Finite-volume analysis
- C. Michael: On-shell transition amplitudes
  - Tune 2-p energies to threshold, Michael [Lat05]
- Small volumes, heavy quarks
Lüscher Method

Map out volume-dependence of energy levels

Resonance “plateau” for weakly interacting system \textit{ie. small width}

Need phase-shift analysis for strongly-coupled systems

2-particle discrete spectrum

Wiese [Lat88]
Spectral Weight

\[ \langle \chi(t)\bar{\chi}(0) \rangle = \sum_{n=0}^{\infty} \lambda_n \bar{\lambda}_n \exp(-E_n t) \]

Single particle states

\[ \lambda_n \bar{\lambda}_n \sim 1 \]

Two particle states

\[ \lambda_n \bar{\lambda}_n \sim L^{-3} \]

In principle, volume dependence of spectral weight can distinguish 1– or 2–particle states.
“Heavy” quark masses

Standard resonances, like rho and Delta, are typically bound at simulation quark masses

Easy to observe rho

Similarly for all other excited states
Quenching and Chiral Extrap.

Potentially large quenching artifacts

Pentaquarks: chiral extrapolation unknown!
Spin-1/2
<table>
<thead>
<tr>
<th>Study</th>
<th>Evidence</th>
<th>$I(J)^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Csikor et al. (2003)</td>
<td>Lightest 5q-state is $0^-$</td>
<td>$0(1/2)^-$</td>
</tr>
<tr>
<td>Sasaki</td>
<td>“$-$”parity above NK, operator small NK overlap</td>
<td>$0(1/2)^-$</td>
</tr>
<tr>
<td>Chiu &amp; Hsieh</td>
<td>Uncertain analysis</td>
<td>$0(1/2)^+$</td>
</tr>
<tr>
<td>Alexandrou &amp; Tsapalis</td>
<td>Volume-independence of spectral weight</td>
<td>$0(1/2)^-$</td>
</tr>
<tr>
<td>Takahashi et al.</td>
<td>V-indep. of spec. weight for 1st excited state</td>
<td>$0(1/2)^-$</td>
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</table>
### Spin-1/2 “Probably not”

<table>
<thead>
<tr>
<th>Study</th>
<th>Evidence (lack of)</th>
</tr>
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<tbody>
<tr>
<td>Mathur et al.</td>
<td>Volume dep. consistent with scattering state</td>
</tr>
<tr>
<td>Ishii et al.</td>
<td>HBC rules out localised 5Q state</td>
</tr>
<tr>
<td>Lasscock et al.</td>
<td>No anomalous states beyond 2-particle spectrum</td>
</tr>
<tr>
<td>Holland &amp; Juge</td>
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</table>
Takahashi et al. PRD(2005)

5Q — ground state

5Q — excited state

$E_{NPK}^{p=1}$

Energy

Extent $L$ [lattice unit]

Spectral Weight

Volume

Spectral Weight

Volume
Hybrid BCs

Ishii et al. PRD(2005)

Local 5Q state ruled out in ground state

$u, d, s$ periodic

$u, d$ antiperiodic

$s$ periodic

$N+K$
Spin-3/2
5Q Bound-state? \[ I(J^\pi) = 0\left(\frac{3}{2}^+\right) \]

Far below threshold!

\[ M \text{ (GeV)} \]

\[ m_\pi^2 \text{ (GeV}^2) \]

Lasscock et al. hep-lat/0504015
Mass-splitting analysis

\[ E_{5Q} - E_{KN} \]

Removed correlated fluctuations

Lasscock et al.

Smaller volume
Coarser lattice

Ishii et al.

hep-lat/0504015

Binding mechanism

\[ \sim 500 \text{MeV} \]
Volume effect?

Potentially stable on larger volumes

\[ E_{5Q} - (m_N + m_K) \]
Summary

- Study of (exotic) resonance physics is a challenging problem for lattice spectroscopy
- No definitive answer, as yet
- Further investigation could be interesting
- Dynamical fermions, please!
References — Pentaquark

Csikor et al., JHEP 0311,070(2003)
Sasaki, PRL93,152001(2004)
Chiu & Hsieh, PRD72,034505(2005)
Mathur et al., PRD70,074508(2004)
Ishii et al., PRD71,034001(2005)
Lasscock et al., PRD72,014502(2005)
Csikor et al., hep-lat/0503012
Alexandrou & Tsapalis, hep-lat/0503013
Takahashi et al., PRD71,114509(2005)
Holland & Juge, hep-lat/0504007
Lasscock et al., hep-lat/0504015
Ishii et al., hep-lat/0506022
U.-J. Wiese, NPB(PS)9,609(1989) [Lat88]
C. Michael, hep-lat/0509023 [Lat05]
RDY et al., PRD66,094507(2002)