The Status of Exotic Meson
Light and Heavy

D.P. Weygand
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I have been using the constituent quark model for many years now as a tool for understanding the spectrum and properties of the low-lying mesons and baryons. For most of this time I have been painfully aware of the difficulty of understanding from first principles (i.e., from QCD) why such a model should work. I have nevertheless had faith that we would eventually be able to justify the use of this model simply because it is such a good representation of the physics.

At the same time, the picture I will propose to rationalize the success of the quark model (which is related to the old string model) leads inevitably to a model for states beyond the quark model: hybrids, glueballs, and multiquark states.
I have been using the constituent quark model for many years now as a tool for understanding the spectrum and properties of the low-lying mesons and baryons. For most of this time I have been painfully aware of the difficulty of understanding from first principles (i.e., from QCD) why such a model should work. I have nevertheless had faith that we would eventually be able to justify the use of this model simply because it is such a good representation of the physics.

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Questions:

Do exotic mesons exist in theory?

Do exotic mesons exist in experiment?
Experiment
Experiment

The Partial Wave Analysis ‘Isobar’ Technique
Experiment

The Partial Wave Analysis ‘Isobar’ Technique

$\pi, K, \gamma$

$p$
The Partial Wave Analysis ‘Isobar’ Technique

Experiment

\[ \pi, K, \gamma \]

\[ X^{JP} \]

\[ \pi, K \]

\[ p, n, \Delta \]

\[ p \]
The Partial Wave Analysis ‘Isobar’ Technique

\[ I(\tau) = \sum_{\epsilon,k} \left( \sum_{\beta} \epsilon V_{k\beta} \epsilon A_{\beta}(\tau) \right)^2 \]
The Partial Wave Analysis ‘Isobar’ Technique

\[ I(\tau) = \sum_{\epsilon, k} \left\{ \sum_{\beta} \epsilon V_{k;\beta} \epsilon A_{\beta}(\tau) \right\}^2 \]
The Partial Wave Analysis ‘Isobar’ Technique

\[ I(\tau) = \sum_{\epsilon,k} \left( \sum_{\beta} \epsilon V_{k\beta} \epsilon A_{\beta}(\tau) \right)^2 \]
The Partial Wave Analysis ‘Isobar’ Technique

\[ I(\tau) = \sum_{\epsilon,k} \left( \sum_{\beta} \epsilon V_{k\beta} \epsilon A_{\beta}(\tau) \right)^2 \]

Experiment

\( p, n, \Delta \)

\( \pi, K, \gamma \)

\( X^{JP} \)

\( \pi, K \)

Isobar
The Partial Wave Analysis ‘Isobar’ Technique

\[ I(\tau) = \sum_{\epsilon, k} \left\{ \sum_{\beta} eV_{k,\beta} e^{A_{\beta}(\tau)} \right\}^2 \]

\[ \mathcal{L} = \left[ \frac{\bar{n}}{n!} e^{-\bar{n}} \right] \prod_{i}^{n} \left[ \frac{I(\tau_i)}{\int I(\tau)\eta(\tau)d\tau} \right] \]
E852 250000 events/1997

\[ \pi^- p \rightarrow \pi^- \pi^- \pi^+ p \]

**Graphs:**

- **Graph (a):**
  - Mass (GeV/c²)
  - Events / (5 MeV/c²)
  - Peaks at \( a_1 \), \( a_2 \), \( \pi_2 \), \( f_2 \)

- **Graph (b):**
  - Mass (GeV/c²)
  - Intensity / (40 MeV/c²)
  - Peaks at \( \rho \)

- **Graph (c):**
  - Mass (GeV/c²)
  - Intensity / (40 MeV/c²)
  - Peaks at \( 2^- \)

- **Graph (d):**
  - Mass (GeV/c²)
  - Intensity / (40 MeV/c²)
  - Peaks at \( 2^{++} \)
Fig. 1. Invariant mass of $\pi^-\pi^-\pi^+$ final states for $0.1 < t' < 1.0 \text{ GeV}^2/c^2$.

Fig. 2. Dalitz plot for $\pi_2(1670)$, selected by a $\pm 1\Gamma$ cut around its nominal mass.
**COMPASS**

CERN-SPS fixed target

2004: 2 days, 190 GeV $\pi^-$ beam  Pb target

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**Fig. 1.** Invariant mass of $\pi^-\pi^-\pi^+$ final states for $0.1 < t' < 1.0 \text{ GeV}^2/c^2$.

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**Fig. 2.** Dalitz plot for $\pi_2(1670)$, selected by a $\pm 1\Gamma$ cut around its nominal mass.
Fig. 1. Invariant mass of $\pi^-\pi^-\pi^+$ final states for $0.1 < t' < 1.0 \text{ GeV}^2/c^2$.

Fig. 2. Dalitz plot for $\pi_2(1670)$, selected by a $\pm 1\Gamma$ cut around its nominal mass.
\[ J^{PC} = 1^{+} \]
• BW parameters for $\pi_1(1600)$
  $M = (1660 \pm 10^{0}_{-64})$ MeV/c$^2$
  $\Gamma = (269 \pm 21^{+42}_{-64})$ MeV/c$^2$

• Leakage negligible: < 5%
\[ \pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb \ (2004) \]

- \( p_\pi = 190 \text{GeV} / c \)
- 4M events (full \( t \) range)
- 450k events in \( 0.1 < t' < 1.0 \ \text{GeV}^2 / c^2 \)

\[ \pi^- p \rightarrow \pi^- \pi^- \pi^+ p \ (2008) \]

- \( p_\pi = 190 \text{GeV} / c \)
- \( \sim 96 \text{M events} \) in \( 0.1 < t' < 1.0 \ \text{GeV}^2 / c^2 \)
COMPASS

π⁻ p → π⁻ π⁻ π⁺ p

0.1 GeV² < t' < 1.0 GeV²
E852

\[ \pi^- p \rightarrow \eta' \pi^- p \]

![Graphs showing data for E852 reaction](image)
$\pi^- p \rightarrow \eta' \pi^- p$

a. $|t|$ distribution

b. $P_+ - D_+$ phase (rad)

c. $P_+$

d. $D_+$

M($\eta'\pi^-$) (GeV/c$^2$)

Events/(0.05 GeV/c$^2$)

Fit 2

Fit 3

c. $P_+ - G_+$ phase

d. $G_+$

e. $G_+$

$\Delta \phi$ (rad)

M($\eta'\pi^-$) (GeV/c$^2$)

Events/(0.1 GeV/c$^2$)
E852  $\pi^- p \rightarrow \eta' \pi^- p$

### Partial Wave

<table>
<thead>
<tr>
<th>Partial Wave</th>
<th>Mass</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_+$</td>
<td>$1.597 \pm 0.010^{+0.045}_{-0.013}$</td>
<td>$0.340 \pm 0.040 \pm 0.050$</td>
</tr>
<tr>
<td>$D_+$</td>
<td>$1.318 \pm 0.008^{+0.003}_{-0.005}$</td>
<td>$0.140 \pm 0.035 \pm 0.020$</td>
</tr>
<tr>
<td>$G_+$</td>
<td>$2.000 \pm 0.040^{+0.063}_{-0.020}$</td>
<td>$0.350 \pm 0.100 \pm 0.050$</td>
</tr>
</tbody>
</table>
COMPASS

$\pi^- p \rightarrow \eta' \pi^- p$  @190 GeV/c

Final state selected: exclusive 3 tracks, 2 photons

Result:

- 18,000 events with $m(\eta' \pi) < 2$ GeV/$c^2$, 35,000 total
- mass reach beyond 2 GeV/$c^2$
- additionally, about 3,000 events in $\pi\eta'$, $\eta \rightarrow 3\pi$ channel
Partial Wave Analysis

**Graphs:**
- **Int. $P_+$**
- **$\Delta \Phi(D_+ - P_+)$**
- **$\Delta \Phi(G_+ - P_+)$**
- **Int. $D_+$**
- **$\Delta \Phi(G_+ - D_+)$**
- **Int. $G_+$**
Partial Wave Analysis

1-(1+)1+ \eta \pi - p

\begin{array}{|c|c|}
\hline
\text{Entries} & 95 \\
\text{Mean} & 1.692 \\
\text{RMS} & 0.2873 \\
\chi^2 / \text{ndf} & 267.2 / 39 \\
\text{Prob} & 8.734e-25 \\
p^0 & 9.195 \pm 50.0 \\
p^1 & 1.6 \pm 0.0 \\
p^2 & -0.293 \pm 0.011 \\
\hline
\end{array}

\text{COMPASS 2008} \quad \pi^0 \rightarrow \eta \pi^0 \\
\text{D}_1(1238) \rightarrow \pi^0 \pi^0 \\
\text{Preliminary Data} 

\text{COUPLING CONSTANT} 

\Delta \Phi(D_1 - P_1)

\Delta \Phi(G_1 - P_1)

\Delta \Phi(G_1 - D_1)

\text{COMPASS 2008} \quad \pi^0 \rightarrow \eta \pi^0 \\
\text{Preliminary Data} 

\text{COUPLING CONSTANT} 

\text{COMPASS 2008} \quad \pi^0 \rightarrow \eta \pi^0 \\
\text{Preliminary Data} 

\text{COUPLING CONSTANT} 

\text{COMPASS 2008} \quad \pi^0 \rightarrow \eta \pi^0 \\
\text{Preliminary Data} 

\text{COUPLING CONSTANT}
Study of the reaction $\pi^-\text{Be} \rightarrow \eta\pi^-\pi^-\pi^+\text{Be}$ in the VES experiment

D. Ryabchikov

Institute for High Energy Physics, Protvino

parallel talk at HADRON2011
Motivation

At VES beam energies ($p_{beam} = 28...36$ GeV) production of negative G-parity final states is dominated by diffraction.

The reaction $\pi^-\text{Be} \rightarrow \eta\pi^-\pi^-\pi^+\text{Be}$, $\eta \rightarrow 2\gamma$ is especially interesting:

- try to study high-mass final states having $J^{PC} = 0^{--}, 1^{++}, 2^{--}, ...$
- try to understand nature of exotic $1^{--}$ partial waves in $f_1(1285)\pi^-$ and $\eta'\pi^-$
- do we observe $\eta(1295)\pi^-$ channel?
- known resonances: $\pi(1800), \pi_2(1670), a_2(1700) \rightarrow \eta 3\pi$
$\eta^- \pi^-$ results
Mass-dependent fit

\[ \rho_{ij} = \sum_{r=1}^{N_r} \left( \sum_k C_{ikr}^c \text{BW}_k(m) \sqrt{\int |\psi_j^c(\tau)|^2 d\tau} \right) \left( \sum_l C_{jlr}^c \text{BW}_l(m) \sqrt{\int |\psi_j^c(\tau)|^2 d\tau} \right)^* \]

"Resonant model"

1^-+
M_1 = 1.640 \pm 0.020, \Gamma_1 = 0.400 \pm 0.050

1^-+
M_1 = 1.530 \pm 0.020, \Gamma_1 = 0.410 \pm 0.040
M_2 = 2.050 \pm 0.030, \Gamma_2 = 0.340 \pm 0.080

2^-+
M_1 = 1.670 \pm 0.024, \Gamma_1 = 0.330 \pm 0.050
M_2 = 1.873 \pm 0.011, \Gamma_2 = 0.167 \pm 0.015
a_2(1320) \eta S
M_2 = 2.040 \pm 0.026, \Gamma_2 = 0.290 \pm 0.070
f_1(1285) \eta D
\chi^2/\text{NDF} = 300.0/(303-39) = 1.14
Conclusions

- PWA in mass bins of $\eta 3\pi$-system demonstrates:
  - dominance of various NPE states
  - significant $f_1(1285)\pi^-$ and many other isobaric decay chains:
    $a_0(980)\rho$, $a_2(1320)\eta$, $a_1(1260)\eta$, $\rho(1450)(\rightarrow \rho\eta)\pi^-$, $a_2(1320)\rho$, ...
  - no $\eta(1295)\pi^-$
  - $\eta'\pi^-$ has $a_2(1320)$ + exotic wave, rather broad structure and no clear structures in high mass 2++
  - very small $0^{++}$, no $\pi(1800) \rightarrow \eta 3\pi$

- Further mass-dependent analysis:
  - Can accommodate broad resonances in $1^{++}$ and $1^{--}$ in 1.5-1.6 GeV region
  - $\pi_2(1670) \rightarrow f_1(1285)\pi^-$ ?? (not VERY clear yet)
  - $\pi_2(1880) \rightarrow a_2(1320)\eta$ values obtained: $M_2=1.873 \pm 0.011$, $\Gamma_2=0.167 \pm 0.015$
    Needed: systematic study + Branchings
  - Non-resonant model - a bit worse description. More natural to explain phase-lock between two very broad amplitudes.
Study of interference of Coulomb and strong diffractive production of $\pi^-\pi^-\pi^+$ systems produced off Pb target at COMPASS

D. Ryabchikov, S. Grabmüller, J. Friedrich

Institute for High Energy Physics, Protvino; Physik-Department, E18 Technische Universität München

HADRON2011 talk
**J^{PC} = 2^{++}** amplitude shows resonant nature in two $t'$ regions. Phase is shifted by $\sim 90^0$ between those two fits.
Primakoff contribution in $\pi^-\text{Pb} \rightarrow \pi^-\pi^-\pi^+\text{Pb}$ in COMPASS 2004 Pilot run
- Sharp Coulomb spike $t' \rightarrow 0$ already in raw data. Statistical subtraction method reveals the specific Primakoff $m(3\pi)$ spectrum (very different from dominating diffractive pattern).
- Detailed study with special PWA:
  - M=1 total mass spectrum found similar to stat. substr. result.
  - M=1 intensities with much narrower $t'$ distribution than expected for strong production → Coulomb contribution
  - M=1 production phases of $a_2$ and $\pi_2$ (relative to M=0) show rapid increase as function of $t'$

- $a_2(1320)$ at $t' < 0.01$ predominantly Primakoff produced
- $\pi_2(1670)$ at $t' < 0.01$ shows both Primakoff and strong contributions
- Interference effects between electromagnetic and strong amplitudes visible
The Search for Exotic Mesons in $\gamma p \rightarrow \pi^+\pi^+\pi^- n$ with CLAS at Jefferson Lab

Craig Bookwalter
on behalf of the CLAS collaboration

Florida State University
Tallahassee, FL USA

XIV International Conference on Hadron Spectroscopy (Hadron2011)
Munich, Germany
June 16, 2011
g6c: Major waves \[ \gamma p \rightarrow \pi^+ \pi^+ \pi^- (n) \]

2.3 pb$^{-1}$
g6c: Major waves \[ \gamma p \rightarrow \pi^+ \pi^+ \pi^- (n) \]
g6c: Major waves  \( \gamma p \rightarrow \pi^+ \pi^+ \pi^- (n) \)

\[
\sigma_{\pi_1} < 13.5 \text{ nb}
\]

\((<2\% \text{ of } a_2)\)

Nozar, et al

\( \gamma p \rightarrow \pi^+ \pi^+ \pi^- (n) \)

\( 2^+ (\rho \pi)_{P,F} \)

\( 2^+ (f \pi)_{S} \)

\( 1^+ (\rho \pi)_{S} \)

\( 1^+ (\rho \pi)_{P} \)

\( \pi_1(1600)? \)

\( 2.3 \text{ pb}^{-1} \)
PWA: $2^{++}$ accepted yields

$2^{++}$ yields

- $2^{++}1^{-}D$
- $2^{++}1^{+}D$

$2^{-+}$ S-wave [$Y=f_2(1270)$] yields

- $2^{-+}1^{+}S$
- $2^{-+}1^{-}S$
- $2^{-+}0^{-}S$

$2^{-+}$ P-wave [$Y=\rho(770)$] yields

- $2^{-+}1^{+}P$
- $2^{-+}1^{-}P$

Yield of $2^{-+} \rightarrow f_2(1270)\pi$ : yield of $2^{-+} \rightarrow \rho(770)\pi \approx 3$
High Energy (> 4.4 GeV) Luminosity: $27 \text{ pb}^{-1} \sim 10 \times g_{6c}$ raw luminosity

$\gamma p \rightarrow \pi^+\pi^+\pi^- n$

**PWA: $1^{-+}$ accepted yields**

- $1^{-+}P$-wave [$Y=\rho(770)$] total intensity
- $1^{-+}P$-wave [$Y=\rho(770)$] total intensity
- $1^{-0}P$-wave [$Y=\rho(770)$] total intensity

- accounts for up to 2% of total intensity
**X(3872)**

**Discovered by Belle (2003)**

\[ B^+ \rightarrow J/\psi \, \pi^+ \pi^- \, K^{\pm} \]


**Confirmed by BaBar, CDF, D0**

\[ J^{PC} = 1^{++} \text{ or } 2^{-+} \]


\[ X(3872) \rightarrow J/\psi \, \pi^+ \pi^- \]

\[ X(3872) \rightarrow J/\psi \, \omega \]  

favors 2^{-+}
Both $J^{PC} = 1^{++}$ and $2^{--}$ are possible
X(3872) at LHC

Y. Gao at Hadron2011

At LHC, the first observations through $X(3872) \rightarrow J/\psi \pi \pi$

CMS

$N_{X(3872)} = 548 \pm 104$ (stat.)

$N_{J/\psi(2S)} = 7346 \pm 155$ (stat.)

$\sqrt{s} = 7$ TeV

$\int L dt = 40$ pb$^{-1}$

LHCb

$\int L dt = 35$ pb$^{-1}$

DPF, August 2011

D.P. Weygand

Thursday, August 11, 2011
X(3872)

V. Bhardwaj, et al.
arXiv:1105.0177v1 [hep-ex]
(2011)
$Y(4260)$

B. Aubert et al. BABAR Collaboration


$e^+ e^- \rightarrow J/\psi \pi^+ \pi^- \gamma \quad J^{PC} = 1^{--}$
$Y(4260)$

B. Aubert et al. BABAR Collaboration


$e^+e^- \rightarrow J/\psi \pi^+ \pi^- \gamma \quad J^{PC} = 1^{--}$

$\ell^+ \ell^- \rightarrow J/\psi \pi\pi \quad (\ell = e)$

CLEO direct scan:
T.E. Coan et al. PRL96,162003 (2006)
Y(4260)

Charmonium gluonic hybrid
Lattice/NRQCD

Molecule/Bound State

Tetraquark

Hadrocharmonium
charmonium state embedded in light hadronic matter

S. Dubynskiy, M.B. Voloshin

Z$^+(4430)$

Discovered by Belle in 2007

Confirmed 2010

\[ B \rightarrow K \pi \psi' \]
\[ Z^+(4430) \rightarrow \pi^+ \psi' \]


Not seen by BaBar (413 fb$^{-1}$), also in J/$\psi$ \pi$^+$ Decay

B. Aubert et al., PRD 79, 112001 (2009)
Charmonium Radiative Decays

other charmonium states are easily accessible from the $\psi(2S)$ (and have many decay modes)
Charmonium Radiative Decays

Charmonium Spectrum

other charmonium states are easily accessible from the $\psi(2S)$ (and have many decay modes)
Charmonium Radiative Decays

\[ \psi(2S) \rightarrow \gamma (\pi^+ \pi^- \rho^+ \rho^-) \]

\[ \psi(2S) \rightarrow \gamma (K_s K^+ \pi^-) \]

(CLEO, not public)

Charmonium Spectrum

\[ \eta_c(2S) \]
\[ \eta_c(1S) \]
\[ \chi_{c0}(1P) \]
\[ \chi_{c1}(1P) \]
\[ \chi_{c2}(1P) \]
\[ \chi_{c0}(2P) \]
\[ \psi(2S) \]
\[ \psi(1S) \]

E1-Dominated Transitions
M1-Dominated Transitions

other charmonium states are easily accessible from the \( \psi(2S) \)
(and have many decay modes)
Charmonium Radiative Decays

- \( \psi(2S) \rightarrow \gamma (\pi^+\pi^-) \)
- \( \psi(2S) \rightarrow \gamma (\eta\pi\pi) \)
- \( \psi(2S) \rightarrow \gamma (K_\ell K^+\pi^-) \)

Other charmonium states are easily accessible from the \( \psi(2S) \) (and have many decay modes)

*CLEO, not public*
Search for $\pi$ exotic states:

$\Rightarrow$ the only $\chi_{c1}$ S-wave decay allowed is

$$\chi_{c1} \rightarrow \pi \pi$$ with $\pi \rightarrow \eta \pi$

Study other dynamics:

$\Rightarrow$ other decays include

<table>
<thead>
<tr>
<th>$\chi_{c1}$ Decay Mode</th>
<th>$L$</th>
<th>Isobar</th>
<th>$J^{PC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0 \pi$; $a_0 \rightarrow \eta \pi$</td>
<td>$P$</td>
<td>0$^{++}$</td>
<td></td>
</tr>
<tr>
<td>$\pi_1 \pi$; $\pi_1 \rightarrow \eta \pi$</td>
<td>$S, D$</td>
<td>1$^{-+}$</td>
<td></td>
</tr>
<tr>
<td>$a_2 \pi$; $a_2 \rightarrow \eta \pi$</td>
<td>$P, F$</td>
<td>2$^{++}$</td>
<td></td>
</tr>
<tr>
<td>$a_4 \pi$; $a_4 \rightarrow \eta \pi$</td>
<td>$F, H$</td>
<td>4$^{++}$</td>
<td></td>
</tr>
<tr>
<td>$f_0 \eta$; $f_0 \rightarrow \pi \pi$</td>
<td>$P$</td>
<td>0$^{++}$</td>
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</tbody>
</table>

(work by Mihajlo Kornicer)
Rich substructure in $\chi_{c1} \rightarrow \eta(\gamma)\pi\pi$

(a) [Graph showing $M^2(\eta\pi)$ vs. $M^2(\eta\pi)$ with peaks at $a_0(980)$ and $a_2(1320)$]

(b) [Graph showing $M^2(\eta\pi)$ vs. Events/125 MeV/$c^2$ with peaks at $a_0(980)$ and $a_2(1320)$]

(c) [Graph showing $M^2(\eta\pi)$ vs. Events/125 MeV/$c^2$ with peaks at $f_2(1270)$ and $f_4(2040)$ and a note for S-wave]

(d) [Graph showing $M^2(\eta\pi)$ vs. $M^2(\eta\pi)$ with peaks at $a_0(980)$ and $\pi_1(1600)$]

(e) [Graph showing $M^2(\eta\pi)$ vs. Events/250 MeV/$c^2$ with peaks at $a_0(980)$ and $\pi_1(1600)$]

(f) [Graph showing $M^2(\eta\pi)$ vs. Events/250 MeV/$c^2$ with peaks at $f_2(1270)$ and a note for S-wave]
Rich substructure in $\chi_{c1} \rightarrow \eta(\gamma)\pi\pi$

(a) $M(\pi\pi)$ vs $M(\eta\gamma)$

(b) $a_0(980)$

(c) $f_2(1270)$

(d) $a_2(1320)$

(e) $f_4(2040)$

(f) $S$-wave

Jefferson Lab
Thomas Jefferson National Accelerator Facility

DPF, August 2011
D.P. Weygand

Thursday, August 11, 2011
The Baseline Fit

Notes:

* the $\pi(1600)$ is preferred over all other fit variations by $\sim 4\sigma$

* the $\pi(1600)$ retains significance when $M(\pi\pi) > 1$ GeV

* $a_0(980) \rightarrow \eta'\pi$ is a first observation

* the $\pi\pi$ S-wave does an “adequate” job describing data (as good or better than a simple $\sigma$ pole)
The Baseline Fit

Notes:

* the $\pi_1(1600)$ is preferred over all other fit variations by $\sim 4\sigma$

* the $\pi_1(1600)$ retains significance when $M(\pi\pi) > 1$ GeV

* $a_0(980) \rightarrow \eta'\pi$ is a first observation

* the $\pi\pi$ S-wave does an "adequate" job describing data (as good or better than a simple $\sigma$ pole)
Highly Excited and Exotic Meson Spectrum from Dynamical Lattice QCD

Jozef J. Dudek, Robert G. Edwards, Michael J. Peardon, David G. Richards, and Christopher E. Thomas

(for the Hadron Spectrum Collaboration)

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School of Mathematics, Trinity College, Dublin 2, Ireland

(Received 13 October 2009; published 31 December 2009)

Using a new quark-field construction algorithm and a large variational basis of operators, we extract a highly excited isovector meson spectrum on dynamical anisotropic lattices. We show how carefully constructed operators can be used to reliably identify the continuum spin of extracted states, overcoming the reduced cubic symmetry of the lattice. Using this method we extract, with confidence, excited states, states with exotic quantum numbers ($0^{--}$, $1^{-+}$, and $2^{+-}$), and states of high spin, including, for the first time in lattice QCD, spin-four states.

DOI: 10.1103/PhysRevLett.103.262001

PACS numbers: 12.38.Gc, 14.40.Cs
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Isovector mesons

\[ m_\pi \sim 700 \text{ MeV} \]
\[ V \sim (2.0 \text{ fm})^3 \]

\[ \pi_2(1670) \]
\[ a_1(1260) \]
\[ a_2(1320) \]

- Positive parity:
  - \[ 1^{++} \]
  - \[ 0^{++} \]
  - \[ 1^{++} 2^{++} 3^{++} 4^{++} \]
  - \[ 3^{--} \]

- Negative parity:
  - \[ 0^{-+} \]
  - \[ 1^{--} 2^{--} 3^{--} 4^{--} \]
  - \[ 2^{--} 4^{--} \]

Box height is statistical uncertainty

References:
Conclusion

- COMPASS 2008/2009: large data sets in diffractive $\pi^-/K^-/p$ dissociation (up to 2 orders of magnitude improvement)
- Charmonium decays: valuable source of light mesons
- Clear evidence for spin-exotic $\pi_1(1600)$:
  - Diffraction vs. photoproduction?
  - Where is the $I = 0$ partner $\eta_1(1600)$?

Outlook

- Improvement of Amplitude Analysis Models
- BES III, COMPASS continue data taking
- GluEx @ JLab Hall-D: Dedicated photoproduction experiment
- Belle II: Charm/Beauty Factory
- PANDA: $\bar{p}p$ annihilation

Thursday, August 11, 2011
Conclusion

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- Charmonium decays: valuable source of light mesons
- Clear evidence for spin-exotic $\pi_1(1600)$:
  - Diffraction vs. photoproduction?
  - Where is the $I = 0$ partner $\eta_1(1600)$?

Outlook

- Improvement of Amplitude Analysis Models
- BES III, COMPASS continue data taking
- GluEx @ JLab Hall-D: Dedicated photoproduction experiment
- Belle II: Charm/Beauty Factory
- PANDA: $\bar{p}p$ annihilation
Conclusion

- COMPASS 2008/2009: large data sets in diffractive $\pi^-/K^-/p$ dissociation (up to 2 orders of magnitude improvement)
- Charmonium decays: valuable source of light mesons
- Clear evidence for spin-exotic $\pi_1(1600)$:
  - Diffraction vs. photoproduction?
  - Where is the $I = 0$ partner $\eta_1(1600)$?

Outlook

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Thank you for inviting me to Providence