Outline of Talk

- Introduction
- Meson Spectroscopy
- Glueballs
  - Expectations
  - Experimental Data
  - Interpretation
- Hybrid Mesons
  - Expectations
  - Experimental Data
- Summary and Future

\[ S = S_1 + S_2 \]
\[ J = L + S \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^L + S \]
Normal Mesons

quark-antiquark pairs

Non-quark-antiquark

0-- 0+- 1-- 2+- 3-- ...

\[ J = L + S \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]
\[ G = C (-1)^{I} \]

\[ ^1S_0 = 0^{-+} \]
\[ ^3S_1 = 1^{--} \]

\[ (2S+1) \frac{L}{J} \]

\[ \rho_3, \omega_3, \phi_3, K_3 \quad 3-- \]
\[ \rho_2, \omega_2, \phi_2, K_2 \quad 2-- \]
\[ \rho_1, \omega_1, \phi_1, K_1 \quad 1-- \]
\[ \pi_2, \eta_2, \eta'_2, K_2 \quad 2^{++} \]

\[ a_2, f_2, f'_2, K_2 \quad 2^{++} \]
\[ a_1, f_1, f'_1, K_1 \quad 1^{++} \]
\[ a_0, f_0, f'_0, K_0 \quad 0^{++} \]
\[ b_1, h_1, h'_1, K_1 \quad 1^{-} \]

\[ \rho, \omega, \phi, K^* \quad 1-- \]
\[ \pi, \eta, \eta', K \quad 0^{--} \]
Each box corresponds to 4 nonets (2 for L=0)

Radial excitations

Exotic nonets

Glueballs

Hybrids

Lattice 1-- 1.9 GeV

0++ 1.6 GeV

(L = q\bar{q} angular momentum)
QCD is a theory of quarks and gluons.

What role do gluons play in the meson spectrum?

Lattice calculations predict a spectrum of glueballs. The lightest 3 have $J^{PC}$ Quantum numbers of $0^{++}$, $2^{++}$ and $0^{-+}$.

The lightest is about $1.6 \text{ GeV}/c^2$.
Glue-rich channels

Where should you look experimentally for Glueballs?

Radiative J/ψ Decays

0⁻⁺ $\eta(1440)$
0⁺⁺ $f_0(1710)$ \{ Large signals \}

Proton-Antiproton Annihilation

Central Production
(double-pomeron exchange)
Decays of Glueballs?

Glueballs should decay in a flavor-blind fashion.

\[ \pi\pi : K\bar{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0 \]

\(\eta\eta'\)=0 is true for any SU(3) singlet and for any pseudoscalar mixing angle. Only an SU(3) “8” can couple to \(\eta\eta'\).

Flavor-blind decays have always been cited as glueball signals. Not necessarily true – coupling proportional to daughter mass can distort this.
Crystal Barrel Results: antiproton-proton annihilation at rest

Discovery of the $f_0(1500)$
Solidified the $f_0(1370)$
Discovery of the $a_0(1450)$

$f_0(1500) \Rightarrow \pi\pi, \eta\eta, \eta', KK, 4\pi$

$f_0(1370) \Rightarrow 4\pi$

Establishes the scalar nonet

700,000 $\pi^0\pi^0\pi^0$ Events

250,000 $\eta\pi^0$ Events
The $f_0(1500)$

Is it possible to describe the $f_0(1500)$ as a member of a meson nonet?

$$
\begin{align*}
\begin{pmatrix} f_0(1370) \\ f_0(1500) \end{pmatrix} &= \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta \cos \theta \end{pmatrix} \begin{pmatrix} 1 \\ 8 \end{pmatrix} \\
\end{align*}
$$

Use SU(3) and OZI suppression to compute relative decays to pairs of pseudoscalar mesons.

Get an angle of about 143°

90% light-quark
10% strange-quark

Both the $f_0(1370)$ and $f_0(1500)$ are $u\bar{u}$ & $d\bar{d}$
WA102 Results

CERN experiment colliding p on a hydrogen target.

Central Production Experiment

Recent comprehensive data set and a coupled channel analysis.

\[
\begin{align*}
\frac{f_0(1370) \rightarrow \pi\pi}{f_0(1370) \rightarrow \pi\pi} &= 2.17 \pm 0.90 \\
\frac{f_0(1370) \rightarrow \pi\pi}{f_0(1370) \rightarrow \pi\pi} &= 0.35 \pm 0.21 \\
\frac{f_0(1500) \rightarrow \pi\pi}{f_0(1500) \rightarrow \pi\pi} &= 5.5 \pm 0.84 \\
\frac{f_0(1500) \rightarrow \eta\eta}{f_0(1500) \rightarrow \eta\eta} &= 0.32 \pm 0.07 \\
\frac{f_0(1500) \rightarrow \eta\eta'}{f_0(1500) \rightarrow \eta\eta'} &= 0.52 \pm 0.16 \\
\frac{f_0(1710) \rightarrow \pi\pi}{f_0(1710) \rightarrow \pi\pi} &= 0.20 \pm 0.03 \\
\frac{f_0(1710) \rightarrow \eta\eta}{f_0(1710) \rightarrow \eta\eta} &= 0.48 \pm 0.14 \\
\frac{f_0(1710) \rightarrow \eta\eta'}{f_0(1710) \rightarrow \eta\eta'} &< 0.05(90\% cl)
\end{align*}
\]
BES Results

$J/\psi \rightarrow \gamma X$

$J/\psi \rightarrow \gamma f_0(1500) \Rightarrow f_0(1500) \rightarrow \pi^+\pi^-$  \hspace{1cm} 0.665 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1500) \Rightarrow f_0(1500) \rightarrow \pi^0\pi^0$  \hspace{1cm} 0.34 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1500) \Rightarrow f_0(1500) \rightarrow \pi^+\pi^-\pi^+\pi^-$  \hspace{1cm} 3.1 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1710) \Rightarrow f_0(1710) \rightarrow \pi^+\pi^-$  \hspace{1cm} 2.64 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1710) \Rightarrow f_0(1710) \rightarrow \pi^0\pi^0$  \hspace{1cm} 1.33 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1710) \Rightarrow f_0(1710) \rightarrow K\bar{K}$  \hspace{1cm} 9.62 $10^{-4}$

$J/\psi \rightarrow \gamma f_0(1710) \Rightarrow f_0(1710) \rightarrow \pi^+\pi^-\pi^+\pi^-$  \hspace{1cm} 3.1 $10^{-4}$

Clear Production of $f_0(1500)$ and $f_0(1710)$, no report of the $f_0(1370)$. $f_0(1710)$ has strongest production.
Model for Mixing

\[ G \rightarrow q\bar{q} \text{ flavor blind?} \quad r \]
\[ u\bar{u}, d\bar{d}, s\bar{s} \]

Solve for mixing scheme

F.Close: hep-ph/0103173
Meson Glueball Mixing

Physical Masses
\( f_0(1370), f_0(1500), f_0(1710) \)

Bare Masses:
\( m_1, m_2, m_G \)

\[
\left( \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} \right)^{(G)} (S) (N)
\]

\[
\begin{align*}
 f_0(1370) & : -0.69 \pm 0.07 & 0.15 \pm 0.01 & 0.70 \pm 0.07 & \sim (|1> - |G)> \\
 f_0(1500) & : -0.65 \pm 0.04 & 0.33 \pm 0.04 & -0.70 \pm 0.07 & \sim (|8> - |G)> \\
 f_0(1710) & : 0.39 \pm 0.03 & 0.91 \pm 0.02 & 0.15 \pm 0.02 & \sim (|1> + |G)> \\
\end{align*}
\]

\[
\begin{align*}
 m_1 & = 1377 \pm 20 \\
 m_2 & = 1674 \pm 10 \\
 m_G & = 1443 \pm 24 \\
\end{align*}
\]

Lattice of about 1600
Glueball Expectations

**Antiproton-proton:** Couples to \((u\bar{u} + d\bar{d})\)
Observe: \(f_0(1370), f_0(1500)\)

**Central Production:** Couples to \(G\) and \((u\bar{u} + d\bar{d})\) in phase.
Observe: \(f_0(1370), f_0(1500),\) weaker \(f_0(1710)\).

**Radiative \(J/\psi\):** Couples to \(G\), \(|1\rangle\), suppressed \(|8\rangle\)
Observe strong \(f_0(1710)\) from constructive \(|1\rangle + G\)
Observe \(f_0(1500)\) from \(G\)
Observe weak \(f_0(1370)\) from destructive \(|1\rangle + G\)

**Two photon:** Couples to the quark content of states, not to the glueball. Not clear to me that \(\gamma\gamma \rightarrow f_0\) has been seen.
Higher mass glueballs?

Lattice predicts that the $2^{++}$ and the $0^{-+}$ are the next two, with masses just above 2GeV/c².

Radial Excitations of the $2^{++}$ ground state
L=3  $2^{++}$ States + Radial excitations
$f_2(1950), f_2(2010), f_2(2300), f_2(2340)\ldots$

2’nd Radial Excitations of the $\eta$ and $\eta'$, perhaps a bit cleaner environment! (I would Not count on it though....)

I expect this to be very challenging. Evidence from BES for an $\eta(1760)\rightarrow\omega\omega$. 
Hybrid Mesons
built on quark-model mesons

ground-state flux-tube
m=0

excited flux-tube
m=1
1++ or 1--

normal mesons

$CP = \{(-1)^L S\} \{(-1)^L + 1\}$
$= \{(-1)^{S+1}\}$

Flux-tube Model
m=0  $CP = (-1)^{S+1}$
m=1  $CP = (-1)^S$

S=0,L=0,m=1
J=1  CP=+
$J^{PC}=1++,1--$
(not exotic)

S=1,L=0,m=1
J=1  CP=-
$J^{PC}=0++,0--$
1++,1--

exotic
2++,2--

$\rho, \omega, \phi$
Gluonic Excitations provide an experimental measurement of the excited QCD potential.

Observations of exotic quantum number nonets are the best experimental signal of gluonic excitations.
Hybrid Predictions

Flux-tube model: 8 degenerate nonets

\[1^{++},1^{--},0^{-+},0^{+-},1^{--},1^{++},2^{-+},2^{++}\] \(\sim 1.9 \text{ GeV}/c^2\)

Lattice calculations --- 1^{-+} nonet is the lightest

UKQCD (97) \(1.87 \pm 0.20\)
MILC (97) \(1.97 \pm 0.30\)
MILC (99) \(2.11 \pm 0.10\)
Lacock (99) \(1.90 \pm 0.20\)
Mei (02) \(2.01 \pm 0.10\)
Bernard (04) \(1.792 \pm 0.139\)

In the charmonium sector:

\[1^{-+} \quad 4.39 \pm 0.08\]
\[0^{+-} \quad 4.61 \pm 0.11\]

Splitting = 0.20
Decays of Hybrids

Decay calculations are model dependent, but the $^3P_0$ model does a good job of describing normal meson decays.

The angular momentum in the flux tube stays in one of the daughter mesons ($L=1$) and ($L=0$) meson.

$L=0$: $\pi, \rho, \eta, \omega, \ldots$
$L=1$: $a, b, h, f, \ldots$

$\pi_1 \rightarrow \pi b_1, \pi f_1, \pi \rho, \eta a_1$

$\eta \pi, \rho \pi, \ldots$ not preferred.

87, 21, 11, 9 MeV (partial widths)
first lattice prediction $\sim 400$ MeV
E852 Results

\[ \pi^- p \rightarrow \eta \pi^- p \quad (18 \text{ GeV}) \]

\[ \pi_1(1400) \]

\[
\begin{align*}
\text{Mass} & = 1370 \pm 16^{+50}_{-30} \quad \text{MeV}/c^2 \\
\text{Width} & = 385 \pm 40^{+65}_{-105} \quad \text{MeV}/c^2
\end{align*}
\]

The \( a_2(1320) \) is the dominant signal. There is a small (few \%) exotic wave.

Interference effects show a resonant structure in \( 1^-+ \).

(Assumption of flat background phase as shown as 3.)
Crystal Barrel Results: antiproton-neutron annihilation

\( \pi_1(1400) \)

- Mass = 1400 ± 20 ± 20 MeV/c^2
- Width = 310±50^{+50}_{-30} \text{ MeV/c}^2

Without \( \pi_1 \) \( \chi^2/\text{ndf} = 3, \text{ with } = 1.29 \)

Same strength as the \( a_2 \).

Produced from states with one unit of angular momentum.

\[ \eta\pi^0\pi^- \]

\[ a_2(1320) \]

\[ a_2(1320)\rho^-(770) \]
Controversy

In analysis of E852 $\eta\pi^0$ data, so evidence of the $\pi_1(1400)$ is inconclusive.

In CBAR data, the $\eta\pi^0$ channel is not conclusive.

Analysis by Szczepaniak shows that the exotic wave is not resonant – a rescattering effect.

The signal is far too light to be a hybrid by any model.

This is not a hybrid and may well not be a state.
E852 Results

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

At 18 GeV/c

**E852 Results**

\[ \pi^+ \pi^- \pi^- \]

\[ M(\pi^+ \pi^- \pi^-) \quad [{\text{GeV}}/c^2] \]

\[ M(\pi^+ \pi^-) \quad [{\text{GeV}}/c^2] \]

to partial wave analysis

suggests

\[ \pi^- p \rightarrow \rho^0 \pi^- p \]

\[ \rightarrow \pi^+ \pi^- \pi^- p \]
An Exotic Signal

Correlation of Phase & Intensity

Leakage From Non-exotic Wave due to imperfectly understood acceptance

Exotic Signal

\[ \pi_1(1600) \]

\[ M(\pi^+\pi^-\pi^-) \quad [\text{GeV} / c^2] \]

\[ 3\pi \quad m=1593^{+8}_{-10} \pm 28 \pm 47 \quad \Gamma=168^{+150}_{-20} \]

\[ \pi\eta' \quad m=1597^{+45}_{-10} \pm 10 \pm 45 \quad \Gamma=340^{+50}_{-40} \]
In Other Channels

1-+ in $\eta'\pi$

The $\pi_1(1600)$ is the dominant signal in $\eta'\pi$.

Mass = $1.597 \pm 0.010$ GeV

Width = $0.340 \pm 0.040$ GeV

$\pi_1(1600) \rightarrow \eta'\pi$

$\pi^- p \rightarrow \eta'\pi^- p$ at 18 GeV/c
In Other Channels

1−+ in $f_1\pi$ and $b_1\pi$

$$\pi^- p \rightarrow \eta\pi^+\pi^-\pi^-p$$

$$\pi_1(1600) \rightarrow f_1\pi$$

Mass = $1.709 \pm 0.024$ GeV

Width = $0.403 \pm 0.08$ GeV

In both $b_1\pi$ and $f_1\pi$, observe Excess intensity at about 2 GeV/c².

Mass ~ 2.00 GeV,

Width ~ 0.2 to 0.3 GeV

$\pi^- p \rightarrow \omega\pi^0\pi^-p$ $\pi_1(1600) \rightarrow b_1\pi$

Mass = $1.687 \pm 0.011$ GeV

Width = $0.206 \pm 0.03$ GeV
\pi_1(1600) \text{ Consistency}

\begin{align*}
3\pi & \quad m=1593 \quad \Gamma=168 \\
\eta'\pi & \quad m=1597 \quad \Gamma=340 \\
f_1\pi & \quad m=1709 \quad \Gamma=403 \\
b_1\pi & \quad m=1687 \quad \Gamma=206
\end{align*}

Not Outrageous, but not great agreement. Mass is slightly low, but not crazy.

Szczepaniak: Explains much of the \eta' signal as a background rescattering similar to the \eta\pi.

Still room for a narrower exotic state.
New Analysis

Add $\pi_2(1670) \rightarrow \rho \pi$ (L=3)
Add $\pi_2(1670) \rightarrow \rho_3 \pi$
Add $\pi_2(1670) \rightarrow (\pi \pi)_S \pi$
Add $a_3$ decays
Add $a_4(2040)$

10 times statistics in each of two channels.

Get a better description of the data via moments comparison

No Evidence for the $\pi_1(1670)$
Exotic Signals

$\pi_1 \quad I^G(J^P) = 1^-(1--)$

$\eta_1 \quad I^G(J^P) = 0^+(1++)$

$K_1 \quad I^G(J^P) = \frac{1}{2} (1^-)$

$\eta'_1 \quad I^G(J^P) = 0^+(1++)$

$\pi_1(1400)$ Width $\sim 0.3$ GeV, Decays: only $\eta\pi$
weak signal in $\pi p$ production (scattering??)
strong signal in antiproton-deuterium.

$\pi_1(1600)$ Width $\sim 0.16$ GeV, Decays $\rho\pi, \eta'\pi, (b_1\pi)$
Only seen in $\pi p$ production, (E852 + VES)

$\pi_1(2000)$ Weak evidence in preferred hybrid modes $f_1\pi$ and $b_1\pi$

NOT A HYBRID

Does this exist?
The right place. Needs confirmation.
Exotics and QCD

In order to establish the existence of gluonic excitations, we need to establish the existence and nonet nature of the $1^{++}$ state. We need to establish at other exotic QN nonets – the $0^{+-}$ and $2^{+-}$.

In the scalar glueball sector, the decay patterns have provided the most sensitive information. I expect the same will be true in the hybrid sector as well.

DECAY PATTERNS ARE CRUCIAL
Summary

The first round of $J/\psi$ experiments opened the door to exotic spectroscopy, but the results were confused. LEAR at CERN opened the door to precision, high-statistics spectroscopy experiments and significantly improved both our understanding of the scalar mesons and the scalar glueball. Pion production experiments at BNL (E852) and VES opened the door to states with non-quark-anti-quark quantum numbers. Recent analysis adds to controversy. CERN central production (WA102) provided solid new data on the scalar sector, and a deeper insight into the scalar glueball.

BES is collecting new $J/\psi$ data. CLEO-c can hopefully add with the $\psi'$ program.
The Future

The GlueX experiment at JLab will be able to do for hybrids what Crystal Barrel and WA102 (together) did for glueballs. What are the properties of static glue in light-quark hadrons and how is this connected to confinement.

The antiproton facility at GSI (HESR) will look for hybrids in the charmonium system - PANDA. May also be able to shed more light on the Glueball spectrum.
Significance of signal.
The Scalar Mesons

What about $2^{++}$ and $0^{-+}$? What about $2^{++}$ and $0^{-+}$?

$J/\Psi$ Decays? $J/\Psi$ Decays?

Awaiting CLEO-c

Crystal Barrel proton-antiproton annihilation

Central Production WA102

Overpopulation Strange Decay Patterns Seen in glue-rich reactions Not in glue-poor

Glueball and Mesons are mixed. Scheme is model dependent.

Three States

- $f_0(1370)$
- $f_0(1500)$
- $f_0(1710)$

$\Psi$ Decays? Awaiting CLEO-c

What about $2^{++}$ and $0^{-+}$? What about $2^{++}$ and $0^{-+}$?
What will we learn?

There may be a signal for hybrid mesons - Exotic quantum numbers - but confirmation requires the observation of a nonet, not just a single state.

Mapping out more than one exotic nonet is necessary to establishing the hybrid nature of the states.

Decay patterns will be useful for the exotic QN states, and necessary for the non-exotic QN states.
Photoproduction of Exotics

Quark spins anti-aligned

A pion or kaon beam, when scattering occurs, can have its flux tube excited

Much data in hand with some evidence for gluonic excitations (tiny part of cross section)

Quark spins aligned

Almost no data in hand in the mass region where we expect to find exotic hybrids when flux tube is excited
Exotics in Photoproduction

\[ \pi_1 \quad I^G(J^{PC})=1^-(1^{-+}) \]
\[ \eta_1 \quad I^G(J^{PC})=0^+(1^{-+}) \]
\[ K_1 \quad I^G(J^{PC})= \frac{1}{2} \ (1^{-}) \]
\[ \eta'_1 \quad I^G(J^{PC})=0^+(1^{-+}) \]

Need to establish nonet nature of exotics: \( \pi \ \eta \ \eta' \)

Need to establish more than one nonet: \( 0^{+-} \quad 1^{--} \quad 2^{+-} \)
Exotic Hybrid Results

$1^{+-} \pi_1(1400)$

$1^{+-} \pi_1(1600)$

$1^{+-} \pi_1(2000)$
0\textsuperscript{+-} and 2\textsuperscript{+-} Exotics

In photoproduction, couple to $\rho$, $\omega$ or $\phi$?

\begin{align*}
    b_0 & \quad I^G(J^{PC})=1^+(0^{+-}) & \omega a_1, \rho f_0, \rho f_1 \\
    h_0 & \quad I^G(J^{PC})=0^-(0^{+-}) & \omega f_0, \omega f_1, \rho a_1 \\
    h'_0 & \quad I^G(J^{PC})=0^-(0^{+-}) & \phi f_0, \phi f_1, \rho a_1 \\
    K_0 & \quad I(J^p)=\frac{1}{2}(0^+) & \square \\

    \text{"Similar to $\pi_1$"}
    \begin{align*}
    \omega \pi & \quad \omega a_1, \rho f_0, \rho f_1 \\
    \omega \eta, \rho \pi, \omega f_0, \omega f_1, \rho a_1 \\
    \phi \eta, \rho \pi, \phi f_0, \phi f_1, \rho a_1 \\

    \text{Kaons do not have exotic QN's}
    \end{align*}
\end{align*}
Strong QCD

See $q\bar{q}$ and $qqq$ systems.

Color singlet objects observed in nature:

Nominally, glue is not needed to describe hadrons.

Focus on “light-quark mesons”

Allowed systems: $gg, ggg, q\bar{q}g, q\bar{q}qq\bar{q}$