An Experimental Overview of Gluonic Mesons

Curtis A. Meyer
Carnegie Mellon University,
Pittsburgh, PA 15213

November 28, 2021

Abstract

In this paper, I review the experimental situation for both glueballs and hybrid mesons. Theoretical expectations are discussed, and a survey of what is known about hybrid mesons and glueballs is undertaken. Good experimental evidence exists for both states with exotic quantum numbers and a glueball which is mixed with the nearby mesons, but a full understanding of these still requires additional information.

1 Introduction

Gluonic mesons are in the broadest sense a $q \bar{q}$ system in which the gluonic field contributes directly to the quantum numbers of the meson. In terms of the simple quark model, all quantum numbers of mesons are determined by the $q \bar{q}$ alone. However, Quantum Chromo Dynamics, (QCD) indicates that this picture is not complete. Lattice QCD calculations predict that both purely gluonic states, (glueballs), and states with the gluonic field carrying angular momentum, (hybrids) should exist. Beyond the lattice, most models which explain observed phenomena also predict such gluonic mesons to be present. A number of the hybrid states are predicted to have $J^{PC}$ quantum numbers which are not accessible to simple $q \bar{q}$ systems, the so-called exotics.

This article will review the experimental situation for gluonic excitations. Of particular interest are states with exotic quantum numbers where two candidates exist. Hybrids with normal quantum numbers are more difficult to discern, as they are likely to mix with nearby normal mesons. It is only
through detailed studies of decay and production that they can be identified. Finally, evidence exists for a $J^{PC} = 0^{++}$ glueball that is strongly mixed with the nearby scalar mesons.

2 The Spectrum of $q\bar{q}$ Mesons

Within the picture of the quark model, mesons are $q\bar{q}$ pairs which have been combined with spin, $S$, orbital angular momentum, $L$, and a possible radial excitation. $S$ can be either 0 or 1, while $L$ can be any non-negative integer. The quantum numbers of the allowed states which are conserved by the strong interaction can be built up from these as given as follows:

\[
\text{Total Spin: } J = |L \oplus S| = |L - S| \cdots |L + S|
\]

\[
\text{Parity: } P = (-1)^{L+1}
\]

\[
\text{C - Parity: } C = (-1)^{L+S}
\]

\[
\text{G - Parity: } G = (-1)^{L+S+I}
\]

The light-quark mesons are built up from $u$, $d$, $s$ and their antiquarks. This yields nine possible $q\bar{q}$ combinations for each set of quantum numbers, (nonets). For the allowed values of $L$ and $S$, Table I lists the nonets of mesons that can be formed. The first listed is the $I = 1$ member, the second and third are the two $I = 0$ members, and the last is the $I = \frac{1}{2}$ member which contains non-zero strangeness. The mass in the last column is the approximate experimental mass of the lightest $I = 0$ member of the nonet.

If one looks at the $J^{PC}$ quantum numbers listed in Table II the following values are missing: $0^{--}, 0^{+-}, 1^{++}, 2^{++}, 3^{++}, \ldots$. Anything identified with one of these quantum numbers falls outside of the normal $q\bar{q}$ picture of the quark model.

3 The Spectrum of Gluonic Mesons

Hybrid meson quantum numbers can be predicted within the flux-tube model [1]. In this picture, the gluonic field forms a flux-tube between the $q\bar{q}$ pair. In it ground state, the tube carries no angular momentum, but it can be excited. The lowest excitation is $L = 1$ rotation which contains two degenerate states, (clock-wise and counter-clock-wise rotations). Linear combinations of
\[ \begin{array}{cccc}
L & S & J^{PC} & \text{Particles} & \text{Mass} \\
0 & 0 & 0^{-+} & \pi, \eta, \eta', K & 0.5 \text{GeV}/c^2 \\
1 & 1 & 1^{--} & \rho, \omega, \phi, K^* & 0.8 \text{GeV}/c^2 \\
1 & 0 & 1^{++} & b_1, h_1, h_1 t, K_1 & 1.2 \text{GeV}/c^2 \\
1 & 0 & 0^{++} & a_0, f_0, f_0, K_0 & 1.4 \text{GeV}/c^2 \\
1 & 1 & 1^{++} & a_1, f_1, f_1, K_1 & 1.3 \text{GeV}/c^2 \\
1 & 2 & 2^{++} & a_2, f_2, f_2, K_2 & 1.3 \text{GeV}/c^2 \\
2 & 0 & 2^{-+} & \pi_2, \eta_2, \eta_2, K_2 & 1.7 \text{GeV}/c^2 \\
1 & 1 & 1^{--} & \rho, \omega, \phi, K^* & 1.7 \text{GeV}/c^2 \\
1 & 1 & 2^{--} & \rho_2, \omega_2, \omega_2, K^* & 1.7 \text{GeV}/c^2 \\
1 & 3 & 3^{--} & \rho_3, \omega_3, \phi_3, K^* & 1.7 \text{GeV}/c^2 \\
3 & 0 & 3^{--} & b_3, h_3, h_3, K_3 & 2.0 \text{GeV}/c^2 \\
1 & 2 & 2^{++} & a_2, f_2, f_2, K_2 & 2.0 \text{GeV}/c^2 \\
1 & 3 & 3^{++} & a_3, f_3, f_3, K_3 & 2.0 \text{GeV}/c^2 \\
1 & 4 & 4^{++} & a_4, f_4, f_4, K_4 & 2.0 \text{GeV}/c^2 \\
4 & 0 & 4^{--} & \pi_4, \eta_4, \eta_4, K_4 & 2.0 \text{GeV}/c^2 \\
1 & 3 & 3^{--} & \rho_3, \omega_3, \phi_3, K_3 & 2.25 \text{GeV}/c^2 \\
1 & 4 & 4^{--} & \rho_4, \omega_4, \eta_4, K_4 & 2.25 \text{GeV}/c^2 \\
1 & 5 & 5^{--} & \rho_5, \omega_5, \phi_5, K_5 & 2.35 \text{GeV}/c^2 \\
\end{array} \]

Table 1: The quantum numbers of the nonets built up from the allowed \( L \) and \( S \) quantum numbers. The quoted mass is that for the lightest isoscalar state in the nonet.

these can be taken such that the tube behaves as if it has \( J^{PC} = 1^{-+} \) or \( J^{PC} = 1^{-+} \). Adding these to the \( L = 0 \) mesons, the quantum numbers listed in Table 2 are obtained. What is of particular interest is that three of the \( J^{PC} \)s, \( 0^{-+}, 1^{-+} \) and \( 2^{+-} \) correspond to non \( \bar{q}q \) combinations.

\[ \begin{array}{cccc}
L = 0, S = 0 & J^{PC} = & 1^{++}, 1^{--}, & a_1, f_1, \rho, \omega, \pi, \eta, \pi_1, \eta_1, \pi_2, \eta_2 \\
L = 0, S = 1 & J^{PC} = & 0^{+-}, 1^{-+}, 2^{+-}, & b_0, h_0, b_1, h_1, b_2, h_2 \\
\end{array} \]

Table 2: The \( J^{PC} \) quantum numbers of hybrid mesons in the flux-tube picture. The given \( L \) and \( S \) couple with the flux tube to produce the listed quantum numbers. The last columns lists the names of the particles in the nonets, the \( \pi_1, b_0 \) and \( b_2 \) correspond to exotic quantum-number nonets.

Within the flux-tube model, all eight hybrid nonets are degenerate. The
Lattice also predicts the existence of a flux-tube forming between a heavy quark-antiquark pair as seen in Figure 1 left. It is also possible to calculate the potentials for the ground state and excited states of the flux-tube [2] as seen in Figure 1 right. Lattice predictions for hybrid mesons masses are shown in Table 3. The exotic $1^{−+}$ nonet is the lightest state with a mass in the range of 1.8 to 2$GeV/c^2$. The splitting between the the $1^{−+}$ and $0^{++}$ nonets is predicted to be about 0.2$GeV/c^2$, (with large errors [3]).

| Reference | Mass $GeV/c^2$ | ΔM $GeV/c^2$ |
|-----------|----------------|--------------|
| UKQCD [4] | 1.87 ± 0.20 | MILC [5] 1.34 ± 0.08 ± 0.20 |
| MILC [5]  | 1.97 ± 0.09 ± 30 | MILC [6] 1.22 ± 0.15 |
| MILC [6]  | 2.11 ± 0.13 | MILC [8] 1.323 ± 0.130 |
| LaSch [8] | 1.9 ± 0.20 | [9] 1.19 |
| [10]      | 2.013 ± 0.026 ± 0.071 |

Table 3: Recent results for $1^{−+}$ hybrid meson masses.

Figure 1: Lattice calculation of the hybrid potential [2].

Predictions for the widths and decays of hybrids are based on model calculations with the results of recent work [11] given in Tables 4 and 5. As
can be seen, the width predictions are fairly open. Most of the $0^{+-}$ exotic nonet are expected to be quite broad. However, both the $2^{+-}$ and the $1^{--}$ nonets are expected to be much narrower. The non-exotic hybrids will be more difficult to disentangle as they are likely to mix with nearby normal $q\bar{q}$ States. The expected decay modes of hybrids involve daughters that in turn decay. This makes the overall reconstruction more complicated, with final states involving from four to seven pseudoscalar mesons.

However, these decays can be used as a guideline when looking for the states. Almost all models of hybrid mesons predict that the ground state ones will not decay to identical pairs of S-wave mesons, and that the decays to an $(L = 0)(L = 1)$ pair is favored. The one unit of angular momentum in the flux–tube remains in the internal orbital angular momentum of one of the daughter $q\bar{q}$ pairs.

| Particle | $J^{PC}$ | Total Width MeV | Large Decays |
|----------|----------|-----------------|--------------|
| $\pi_1$  | $1^{+-}$ | $81 - 168$      | $b_1\pi, \rho\pi, \eta(1295)\pi$ |
| $\eta_1$ | $1^{+-}$ | $59 - 158$      | $a_1\pi, \pi(1300)\pi$ |
| $\eta_1'$| $1^{+-}$ | $95 - 216$      | $K_1(1400)K, K_1(1270)K, K^*K$ |
| $b_0$    | $0^{+-}$ | $247 - 429$     | $\pi(1300)\pi, h_1\pi$ |
| $h_0$    | $0^{+-}$ | $59 - 262$      | $b_1\pi$ |
| $h_0'$   | $0^{+-}$ | $259 - 490$     | $K(1460)K, K_1(1270)K$ |
| $b_2$    | $2^{+-}$ | $5 - 11$        | $a_2\pi, a_1\pi, h_1\pi$ |
| $h_2$    | $2^{+-}$ | $4 - 12$        | $b_1\pi, \rho\pi$ |
| $h_2'$   | $2^{+-}$ | $5 - 18$        | $K_1(1400)K, K_1(1270)K, K^*_0(1430)K$ |

Table 4: Exotic quantum number hybrid width and decay predictions.

Glueballs are nominally states of only gluons and are SU(3) singlets. The best predictions for the glueball spectrum comes from the lattice. A recent calculation using and anisotropic lattice [2] is shown in Fig 2. The lightest glueball is expected to have $J^{PC} = 0^{++}$, followed by a $2^{++}$ state and then a $0^{+-}$ state. Unfortunately, all of these quantum numbers are those of normal mesons. In fact the lightest glueball with exotic or non–$q\bar{q}$ quantum numbers is the $2^{+-}$ near 4 GeV/$c^2$ and the $0^{+-}$ state near 4.5 GeV/$c^2$. Both well beyond the mass regime that we consider for light–quark mesons and deep into the charmonium region. The lightest glueballs will appear as an extra $f_0$, $f_2$ and $\eta$ states that don’t fit into a normal nonet. But these extra states
Table 5: Non-exotic quantum number hybrid width and decay predictions.

are likely to be mixed with the two isoscalar states in the normal $q\bar{q}$ nonets.

If we first consider the scalar glueball, ($J^{PC} = 0^{++}$), we find that the lattice prediction for the pure glueball state is $m = (1\, 6.6 \pm 0.3)\text{ GeV}/c^2$. This is extremely close to the nonet of scalar mesons, $a_0(1450)$, $f_0(1370)$, and $K^*_0(1430)$. To establish such a state as a glueball, we will first need to find a third isoscalar state in the same mass regime. A detailed study of productions mechanisms and decays then needs to be carried out. The naive predictions for the pure glueball decay to pairs of pseudoscalar mesons is shown in Table 1. Under the assumption that the glueball couples equally to all pairs of octet and singlet mesons, the following relationships are obtained.

$$\Gamma(G \to \pi\pi : K\bar{K} : \eta \eta : \eta\eta' : \eta'\eta') = 3 : 4 : 1 : 0 : 1$$  \hspace{1cm} (1)

However, in comparing glueball decays to normal mesons decays, we need to allow for the possibility that the glueball coupling to mesons might be different from that of a meson coupling to mesons.

In looking for glueballs, there are certain production reactions which are considered to be glue rich, and others that are considered to be glue poor. The
Figure 2: A lattice calculation of the glueball mass spectrum [13]. The lightest three glueballs have quantum numbers $0^{++}$, $2^{++}$ and $0^{-+}$. The lightest exotic glueball has quantum numbers of $2^{+-}$ with a mass above $4 GeV/c^2$.

Former include $J/\psi$ decays, double-pomeron exchange reactions and proton-antiproton annihilations. The latter include two-photon production and photoproduction. Comparing production rates across a number of such reactions is crucial in establishing the gluonic nature of an observed state.
4 Experimental Status of Hybrids

The most striking experimental prediction for hybrid mesons is the fact that several of the nonets have non-$$q\bar{q}$$ quantum numbers, and the lightest of these will be $$1^{-+}$$, or exotic. Over the last decade, several credible reports of such states have been published. An isospin 1 object, the $$\pi_1(1400)$$ was first reported in $$\pi^- p \rightarrow \eta\pi^- p$$ [14]. This state was quickly confirmed in antiproton-neutron annihilation [15]. Figure 3 shows the Dalitz plot from the latter analysis where the exotic signal is of the same strength as the $$a_2(1320)$$. The PDG [16] lists the mass as $$m = 1.376 \pm 0.017 \text{ GeV}/c^2$$ and the width as $$\Gamma = 0.300 \pm 0.040 \text{ GeV}/c^2$$ with observed decays to $$\pi^- \eta$$ and $$\pi^0 \eta$$.

![Figure 3: The left hand figure shows the Dalitz plot for $$\bar{p}d \rightarrow \eta\pi^-\pi^0 p$$ with both the $$a_2(1320)$$ and the $$\rho(770)$$ indicated. The right hand figure shows the contribution of the $$\pi_1(1400)$$ to the Dalitz plot.]

A second such state, the $$\pi_1(1600)$$, was first observed in $$\pi^- p \rightarrow \pi^+\pi^-\pi^- p$$ [17]. The signal for the $$\pi(1600)$$ is shown in Figure 4. A latter observation reported the $$\pi_1(1600) \rightarrow \eta'\pi$$ [18] and various reports have been made at conferences about other observed decay modes. The VES experiment [19] reports the ratios of: $$b_1\pi : \eta'\pi : \rho\pi = 1 : 1.0 \pm 0.3 : 1.6 \pm 0.4$$. The PDG [16] lists the mass as $$m = 1.596^{+0.025}_{-0.014} \text{ GeV}/c^2$$ and the width as $$\Gamma = 0.312^{+0.064}_{-0.024} \text{ GeV}/c^2$$. Recently there has been a report of the $$f_1(1285)\pi$$ decay mode of the $$\pi(1600)$$ as well third $$\pi_1$$ state in the 1.9 GeV/c^2 region, also decaying to $$f_1\pi$$ [20].

The precise interpretation of these states is still open. The $$\pi_1(1400)$$ is
Figure 4: Data from the E852 experiment showing an exotic $1^{--}$ signal in the $\rho \pi$ subsystem of $\pi^- p \rightarrow \pi^+ \pi^- p$. (a) shows the intensity of the $1^{--}$ signal which interferes with (b) the $2^{++} \pi_2(1670)$. (c) shows the phase difference between the two waves, and (d) has the individual phases, with 1 corresponding to the $1^{--}$, 2 to the $2^{++}$ and 3 to a background term.

significantly lighter than theoretical expectations, and its only observed decay mode, $\eta \pi$ is not expected for a hybrid. Recent work suggests that this state may actually be non-resonant scattering similar to the S-wave $\pi \pi$ scattering at low energy [21]. The same explanation in the $\pi \eta'$ system can also be invoked to explain a large part of the $\eta' \pi$ signal for the $\pi_1(1600)$ [22]. The $\pi_1(1600)$ as seen in $\rho \pi$ is still somewhat lower than theoretical expectations in mass, but could well be a hybrid meson. The open question now is what are its decay modes, and can we find any of its partner states, $\eta_1$ and $\eta_1'$?

There is also a more general issue of what is causing the over population of $\pi_1$ states? There is one $1^{--}$ hybrid nonet, meaning that there should only be one $\pi_1$ state. While it is possible that the $\pi_1(1400)$ is just final state interactions, if there are really two states beyond this, ($\pi_1(1600)$ and $\pi_1(1900)$), it will be necessary to rethink what is happening.
Hybrids with non-exotic quantum numbers are more difficult to discern as they look like normal $q\bar{q}$ mesons. Table 5 shows the widths and decays expected for these states from model calculations. If one assumes that the $\pi_1(1600)$ sets the mass scale for the hybrids, then we are looking in the 1.6 to 2.2 $GeV/c^2$ mass range.

In the $J^{PC} = 0^{-+}$ system, we expect radial excitations of the pseudoscalar mesons as well as a glueball state. Three states of interest appear in this sector, the $\pi(1800), \,(m = 1.8, \Gamma = 0.21)$ has been observed with decays into $f_0(980)\pi, \,(m = 1.8, \Gamma = 0.21)$ has been observed with decays into $f_0(980)\pi, \, f_0(1500)\pi$. and there has been speculation that due to its coupling to scalars, it may have a large hybrid component. The $\eta(1760)$, which decays into $4\pi$, has only been observed in $J/\psi$ decays. This is a likely partner for the $\pi(1800)$. Finally, the $\eta(2225), \,(m = 2.2, \Gamma = 0.15)$ has been observed in $J/\psi$ with decays into $\phi\phi$. This state is too high in mass to be the simple partner of the other two, but is consistent with what is expected of a glueball but needs confirmation.

In the $J^{PC} = 1^{--}$ system, we expect to see the radial excitations of the vector mesons as well as the $^3D_1$ nonet. The mass scale for the D-wave mesons are set by the $^3D_3$ nonet, $\rho(1690), \, \omega(1670)$ and the $\phi(1850)$. There are a rather large number of known states in this region. The $\rho(1450), \, \rho(1700), \, \rho(1900), \, \rho(2150), \, \omega(1420), \, \omega(1650), \, \phi(1680)$. This sector is probably completely mixed, so disentangling it is going to require a clear understanding of other sectors.

The $J^{PC} = 1^{+-}$ hybrid nonet is near the radial excitations of the $b_1$s nonet. One known state exists, the $h_1(1595), \,(m = 1.6, \Gamma = 0.38)$, but little is known it. It is probably consistent with being a radial excitation of the $h_1(1170)$.

The $J^{PC} = 1^{++}$ nonet has the same quantum numbers as the radial excitations of the $a_1$s nonet. One known state exists, the $a_1(1640)$ which has been observed in a $3\pi$ decay. What little is known is consistent with this being a radial excitation of the $a_1(1260)$.

The $J^{PC} = 2^{-+}$ nonet can overlap with the D-wave nonet, $^1D_2$. There are a rather large number of candidates here. The $\pi_2(1670)$ and the $\eta_2(1645)$ are reasonably consistent with the D-wave mesons. There is a second $\eta_2$, the $\eta_2(1870)$ that mass-wise is consistent with being the $\eta'$ of this nonet. However, its decay modes are consistent with it being composed of mostly non-strange light quarks. In fact, the $a_2\pi$ decay appears to be the largest mode for both the $\eta_2(1645)$ and the $\eta_2(1870)$. This sector has the strongest evidence for a hybrid state.
In any case, establishing the non-exotic hybrid nonets will almost certainly require more exotic states. These will allow us to both set the mass scale, and understand the actual decay patterns of the states.

5 Experimental Status of Glueballs

In Fig. 5 are shown the Dalitz plots for $p\bar{p}$ annihilation at rest into $\pi^0\pi^0\pi^0$ and $\pi^0\eta\eta$. While the analysis of these channels involve many intermediate resonances [23, 24], there is one new state which stands out in both, the $f_0(1500)$. This state has a mass of 1.505 GeV/$c^2$ and a width of 0.110 GeV/$c^2$. In later analysis [25, 26], the $f_0(1500)$ has also been observed in the $\eta\eta'$ and $K_LK_L$ final states. Examining all these data, it is possible to extract many different annihilation–decay rates for the $f_0(1500)$ as given in Table 6. We can convert the numbers in this table into relative decay amplitudes squared, $\gamma^2$, which if normalized to the $\eta\eta$ mode are yield the rates given in Table 8. These rates are not consistent with either a pure mesons or a pure glueball and yielded the first evidence that something interesting is happening in the scalar sector.

![Figure 5: Dalitz plots for $\bar{p}p$ annihilation at rest into $3\pi^0$ (left) and $2\pi^0\eta$ (right). The resonances as observed in the partial wave analysis are indicated on the figure.](image)

Another glue-rich channel is that of central production, and a great deal of analysis has been done recently by the WA102 collaboration at CERN.
They have looked at central production of $\pi^+\pi^-$ [27, 28], $\pi^0\pi^0$ [29], $K\bar{K}$ [30], $\eta\eta$ [31] and $\pi^+\pi^-\pi^+\pi^-$ [27, 32, 33] in 450 GeV/c pp collisions. In all of these analysis, they observe two scalar states, the $f_0(1500)$ and the $f_0(1710)$. In addition, in the $4\pi$ data, they observe the $f_0(1370)$. They also find that by kinematically selecting on their data, they were able to enhance the scalar signals.

| State | Mass GeV/c^2 | Width GeV/c^2 | Decay | Reference |
|-------|--------------|---------------|-------|-----------|
| $f_0(980)$ | 0.985 ± 0.010 | 0.065 ± 0.020 | $K^+K^-$ | [30] |
| $f_0(980)$ | 0.982 ± 0.003 | 0.080 ± 0.010 | $\pi^+\pi^-$ | [28] |
| $f_0(1370)$ | 1.290 ± 0.015 | 0.290 ± 0.030 | $\pi^+\pi^-\pi^+\pi^-$ | [32] |
| $f_0(1370)$ | 1.308 ± 0.010 | 0.222 ± 0.020 | $\pi^+\pi^-$ | [28] |
| $f_0(1500)$ | 1.502 ± 0.010 | 0.131 ± 0.015 | $\pi^+\pi^-$ | [28] |
| $f_0(1500)$ | 1.497 ± 0.010 | 0.104 ± 0.025 | $K^+K^-$ | [30] |
| $f_0(1500)$ | 1.510 ± 0.020 | 0.120 ± 0.035 | $\pi^+\pi^-\pi^+\pi^-$ | [32] |
| $f_0(1710)$ | 1.700 ± 0.015 | 0.100 ± 0.025 | $K^+K^-$ | [30] |
| $f_0(2000)$ | 2.020 ± 0.035 | 0.410 ± 0.050 | $\pi^+\pi^-\pi^+\pi^-$ | [32] |

Table 7: Observed scalar mesons in various final states in WA102.

| Decay Rate | $\pi\pi$ | $KK$ | $\eta\eta$ | $\eta'\eta'$ | $4\pi$ |
|------------|---------|------|------------|-------------|-------|
| $f_0(1500)$ | 5.13 ± 1.95 | 0.708 ± 0.209 | 1.00 | 1.64 ± 0.62 | 13.7 ± 4.4 |
| Meson | 14 | 1.4 | 1 | 2.4 | |
| Glueball | 3 | 4 | 1 | 0 | Large |

Table 8: Relative decay amplitudes squared, $\gamma^2$ normalized to the $\eta\eta$ rate for the $f_0(1500)$. These are compared to the SU(3) prediction for an $s\bar{s}$ meson with mixing angle of 150°, as well as for a pure glueball.
A recent analysis of all available information on scalar decays [34] comes up with a plausible mixing scenario that explains the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. It is based on a model that allows for three different decay couplings, and possible flavor violations in glueball decays. This analysis finds bare masses for the scalar glueball of $m_G = 1.443 \pm 0.024 \text{GeV}/c^2$, that of the $u\bar{u}/d\bar{d}$ meson of $m_N = 1.377 \pm 0.020 \text{GeV}/c^2$ and the $s\bar{s}$ meson at $m_S = 1.674 \pm 0.010 \text{GeV}/c^2$. The mixing scheme for each of the three physical states is given below and is graphically shown in Figure 6.

While the precise mixing angles may not be fully pinned down, there are some interesting trends. The central mass state, $f_0(1500)$ has $s\bar{s}$ and $u\bar{u}/d\bar{d}$ out of phase, while the upper and lower states have them in phase. The glueball component is in-phase with the SU(3) singlet piece for the $f_0(1710)$, and out of phase for the $f_0(1370)$. Lastly, the glueball is distributed over all three states. The upper state is mostly $s\bar{s}$, while the lower two contain mostly $u\bar{u}$ and $d\bar{d}$.

While there appears to be solid evidence for a scalar glueball mixed into the scalar nonet, the evidence for the $2^{++}$ and $0^{-+}$ glueballs is significantly weaker. The tensor state is supposed to be next lightest with a predicted mass of about $2.2 \text{GeV}/c^2$. A possible candidate, the $f_2(1950)$ has been observed in
central production in a similar fashion to the scalar glueball candidates \textsuperscript{33}, although there is little other information about this state. A second state, the $\xi(2220)$ was originally reported in $J/\psi$ radiative decays. This very narrow object ($\approx 0.02GeV/c^2$) was originally seen by one experiment \textsuperscript{35}, but not confirmed by several others. No spin parity analysis is available, but $2^{++}$ is favored. It was later seen in the BES experiment \textsuperscript{36} with approximately equal strength in $\pi\pi$, $KK$ and $\bar{p}p$ annihilations. Later careful searches in $\bar{p}p$ annihilation \textsuperscript{37} showed no evidence of this state. These data lead to a lower limit of $J/\psi \rightarrow \gamma \xi$ of $\approx 2.3 \times 10^{-3}$ \textsuperscript{38}. If this state really exists, it has one of the largest radiative branching fractions in $J/\psi$ decays. The existence of this state is still an open question. Evidence for the $0^{-+}$ glueball is even weaker, and full exploration of the glueball sector awaits new data.

6 Summary

Clear experimental evidence exists for both mesons with non-$q\bar{q}$ quantum numbers and for a scalar glueball which is mixed with the nearby scalar mesons. Unfortunately, the exact nature of the exotic states remain unclear. Their observed mass and decay modes do not completely agree with theoretical expectations, which may well indicate that there are problems with the theory. In order to resolve these issues, it will be necessary to observe and measure both the partners of the existing states as well as states with other exotic quantum numbers. This will be studied in the light quark sector with the GlueX Experiment at Jefferson Lab \textsuperscript{39} and in the charmonium sector with the PANDA experiment at GSI \textsuperscript{40}.

While there is a good explanation of the scalar glueball, a full understanding of the glueballs will require the discovery and study of at least one additional state. There is a very good chance that this will be accomplished with the CLEO-c experiment in the near future \textsuperscript{41}.
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