The Experiemntal Status of Glueballs

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Abstract. In this paper, I review the experimental situation for glueballs. These and other resonances with large gluonic components are predicted as bound states by Quantum Chromodynamics (QCD). The lightest (scalar) glueball is estimated to have a mass in the range from 1 to 2 GeV/c^2; a pseudoscalar and tensor glueball are expected at higher masses. Many different experiments exploiting a large variety of production mechanisms have presented results in recent years on light mesons with $J^{PC} = 0^{++}$, 0^{-+}, and 2^{++} quantum numbers. Good evidence exists for a scalar glueball which is mixed with nearby mesons, but a full understanding is still missing. Evidence for tensor and pseudoscalar glueballs are weak at best.

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INTRODUCTION

While we believe that Quantum Chromodynamics (QCD) is the correct description of the interactions of quarks and gluons, it is a theory that is very difficult to solve in the low-energy regime – that which describes the particles of which the universe is made. This is changing with advances that have been made in Lattice QCD, and the access to ever faster computers. Within QCD, one of the perplexing issues has been the existence of gluonic excitations. In the meson sector, nearly all the observed states can be explained as simple $q\bar{q}$ systems, with the naive quark model both providing a very good explanation for these particles, as well as providing a nice framework in which they can be described.

Both phenomenological models and lattice calculations predict that there should exist additional particles in which the gluons themselves can contribute to the quantum numbers of the states. These include the pure-glue objects known as glueballs as well as $q\bar{q}$ states with explicit glue, known as hybrid mesons. Some of these latter states are expected to have quantum numbers which are forbidden to $q\bar{q}$ systems – exotic quantum numbers which can provide a unique signature for the existence of such particles.

Over the last decade, a great deal of new experimental data on mesons has been collected. This new information bears directly on both the search for, and our current understanding of gluonic excitations of mesons, in particular glueballs and hybrids. In this paper, I will focus on glueballs, rather than gluonic excitations in general.

MESON SPECTROSCOPY

This section briefly describes the simple quark model for mesons in order to facilitate the discussion of expectations for gluonic excitations. A meson consists of a $q\bar{q}$ system, which because it contains both a particle and an antiparticle, has intrinsic negative parity, $P = -1$. The total parity of such a system is given as $P = -(-1)^L$, where L is the orbital angular momentum in the $q\bar{q}$ system. Because quarks have spin $\frac{1}{2}$, the total spin of such a system can be either $S = 0$ or $S = 1$, which leads to a total angular momentum $J = L + S$, where the sum is made according to the rules of addition for angular momentum. In addition, there is also C-parity, or charge conjugation, which for a $q\bar{q}$ system is $C = (-1)^{(L+S)}$.

If only the three lightest quarks, u, d and s, are considered, then nine $q\bar{q}$ combinations can be formed, all of which can have the same S, L and J. They can be represented in spectroscopic notation, ${}^{2S+1}L_J$, or as states of total spin, parity and for the neutral states, charge conjugation: J^{PC}. In each of these nonets, there are two $I = 0$ mesons. Since SU(3) is broken, these two mesons are usually admixtures of the singlet, $|\,1\,\rangle = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$, and octet, $|\,8\,\rangle = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$, states. In nature, the physical states (f and f') are mixtures, where the degree of mixing is given by an angle θ:

$$f = \cos\theta\ |\,1\,\rangle + \sin\theta\ |\,8\,\rangle \tag{1}$$

$$f' = \cos\theta\ |\,8\,\rangle - \sin\theta\ |\,1\,\rangle\,. \tag{2}$$

For the vector mesons, ω and ϕ, one state is nearly pure light-quark ($n\bar{n}$) and the other is nearly pure $s\bar{s}$. This is known as ideal mixing and occurs when $\tan\theta = 1/\sqrt{2}$.

Measuring the masses and decay rates of mesons can be used to identify the quark content of a particular meson. The lightest glueballs have J^{PC} quantum numbers of normal mesons and would appear as an SU(3) singlet state. If they are near a nonet of the same J^{PC} quantum numbers, they will appear as an extra f-like state. While the fact that there is an extra state is suggestive, the decay rates and production mechanisms are also needed to unravel the quark content of the observed mesons.

THE SCALAR GLUEBALL

The $J^{PC} = 0^{++}$ $(L = 1,\ S = 1)$ scalar sector is without doubt the most complex one and the interpretation of the states' nature and nonet assignments are still very controversial. In particular, the number of observed $I = 0$ isosinglet states with masses below 1.9 GeV/c^2 is under debate. According to the PDG mini-review on non-$q\bar{q}$ candidates [1], five isoscalar resonances are well established: the very broad $f_0(600)$ or so-called σ state, the $f_0(980)$, the broad $f_0(1370)$, and the rather narrow $f_0(1500)$ and $f_0(1710)$ resonances. Naive arguments without chiral symmetry constraints and the close proximity of states in other J^{PC} nonets suggest that the $f_0(600)$, $f_0(980)$, and $a_0(980)$ are members of the same nonet. The missing $I = 1/2$ state – usually called $K_0^*(800)$ or κ – is not listed by the Particle Data Group as well established state in its latest 2008 edition. The nature of this nonet is not necessarily $q\bar{q}$. Very often, $f_0(980)$ and $a_0(980)$ are interpreted as multi-quark states or $K\bar{K}$ molecules [2, 3].

Using the same naive arguments, the $a_0(1450)$, $K^*(1430)$, and two states out of the $I = 0$ group, $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$, would form an SU(3) flavor nonet. These nonet assignments however pose some serious challenges. While almost all models agree

TABLE 1. The $I=0$, $J^{PC}=0^{++}$ mesons as listed by the Particle Data Group [1]. Resonances marked with $*$ are listed in the Meson Summary Table.

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ $*$	$400-1200$	$600-1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ $*$	980 ± 10	$40-100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ $*$	$1200-1500$	$200-500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ $*$	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ $*$	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$

on the $K^*(1430)$ to be the quark model $s\bar{u}$ or $s\bar{d}$ state, the situation is very ambiguous for the isoscalar resonances. The most striking observation is that one f_0 state appears supernumerary, thus leaving a non-$q\bar{q}$ (most likely) glueball candidate. Both the $f_0(1370)$ and $f_0(1500)$ decay mostly into pions. In fact, all analyses agree that the 4π decay mode accounts for at least half of the $f_0(1500)$ decay width and dominates the $f_0(1370)$ decay pointing to a mostly $n\bar{n}$ content of these states. On the other hand, the LEP experiments indicate that the $f_0(1500)$ is essentially absent in $\gamma\gamma\to K\bar{K}$ (L3 collaboration [4]) and $\gamma\gamma\to\pi^+\pi^-$ (ALEPH [5]). If the state were of $q\bar{q}$ nature, the extremely small upper limit for the branching fraction into $\pi^+\pi^-$ would suggest a mainly $s\bar{s}$ content [6].

This contradiction emphasizes the non-$q\bar{q}$ nature of the $f_0(1500)$ resonance and makes it a potential glueball candidate. On the other hand, the observed decays into $\pi\pi$, $\eta\eta$, $\eta\eta'$, and $K\bar{K}$ are not in agreement with predictions for a pure glueball. For this reason, a large variety of mixing scenarios of the pure glueball with the nearby $n\bar{n}$ and $s\bar{s}$ isoscalar mesons has been described in the literature.

Mixing in the Scalar Sector

It is generally assumed that the three bare states mix to yield the three physical states. Inputs to such calculations include the masses of the physical states as well as their decay rates into pairs of pseudoscalar mesons. The physical states (f_0 mesons) can be written in terms of the ideally mixed $q\bar{q}$ states:

$$\begin{pmatrix} \mid f_1\,\rangle \\ \mid f_2\,\rangle \\ \mid f_3\,\rangle \end{pmatrix} = \begin{pmatrix} M_{1n} & M_{1s} & M_{1g} \\ M_{2n} & M_{2s} & M_{2g} \\ M_{3n} & M_{3s} & M_{3g} \end{pmatrix} \cdot \begin{pmatrix} \mid n\bar{n}\,\rangle \\ \mid s\bar{s}\,\rangle \\ \mid G\,\rangle \end{pmatrix} \tag{3}$$

While the amount of information from mixing, and the various models that went into creating these are a bit overwhelming, there are some interesting trends in the results. In particular, in the case where one assumes that the bare glueball is heavier than the $s\bar{s}$ state, all of the models support a picture in which the $f_0(1370)$ is mostly the SU(3) singlet state, the $f_0(1500)$ is mostly the SU(3) octet state, and the glueball is dominantly in the $f_0(1710)$ state. In the case where the bare glueball is lighter than the $s\bar{s}$ state, the octet and glueball assignments switch, but there is stronger mixing between the components.

Perhaps most significant in the scalar sector is the question of the existance of the $f_0(1370)$. Under the assumption that the $f_0(1370)$ exists, and the scalar states with masses below 1 GeV/c^2 are of a different origin, the mixing scenario can provide a good description of the data, and makes it very likely that the scalar glueball exists and is manifested in these states. Unfortunately, the exact mixing scheme depends on the models used to describe glueball decays. There is some hope that better information on two-photon couplings to the scalar states as well as more information from heavier systems decaying into scalars may provide some additional insights on the problem.

THE PSEUDOSCALAR GLUEBALL

Evidence for a pseudoscalar glueball is very weak. Within the pseudoscalar sector, the ground states are the well established $\eta(548)$ and $\eta'(958)$. Beyond the simple quark model, a nonet of hybrid pseudoscalar mesons is expected in the 1.8 to 2.2 GeV/c^2 mass region, and a glueball is expected in the ~ 2 GeV/c^2 region. Three additional states below 2 GeV/c^2 are listed in the PDG summary table [1]: $\eta(1295)$, $\eta(1405)$, and $\eta(1475)$. The $\eta(1295)$ and the $\eta(1475)$ are often considered radial excitations of the η and η', respectively, leaving the $\eta(1405)$ as a potential glueball candidate.

While the two pseudoscalar states near 1400 MeV/c^2 are listed by the PDG, there has been some speculation by Klempt [7] that they are in fact a single state with a node in the wave function. There is also some speculation [7] that the $\eta(1295)$ may not exist. In its clearest observations, it is always seen in conjunction with the $f_1(1285)$ and it could possibly be explained as feed through from the 1^{++} state.

The possible non-existance of the $\eta(1295)$ has also been discussed in [8]. The original DM2 [9] observation has not been confirmed by any of the later J/ψ experiments, even with higher statistics. It also appears that while the higher mass pseudoscalers are strongly produced in $p\bar{p}$ annihilation, no evidence of the $\eta(1295)$ is observed. The only other observations of the $\eta(1295)$ are always in conjunction with the nearby $f_1(1285)$. Without a confirmation of the $\eta(1295)$, I feel that one is unable to associate the pseudoscalar glueball with the $\eta(1405)$. There is hope that new data from BES-III and COMPASS will be able to help clarify the situation.

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