ABSTRACT

In this contribution I discuss recent experimental developments in the spectroscopy of higher-mass mesons, especially candidate radial excitations discussed at the WHS99 meeting in Frascati.

1 Introduction: Why radials?

We now have strong evidence for a true $J^{PC} = 1^{-+}$ exotic at 1.6 GeV in $\rho \pi$ at BNL and VES, and $\eta' \pi$ and $b_1 \pi$ at VES, and with a possible lighter state at 1.4 GeV in $\eta \pi$ reported by BNL and Crystal Barrel. Hadron spectroscopy may have finally found the hybrid mesons anticipated by theorists. Of course there is an unresolved concern that these experimental masses are somewhat lighter than theoretical expectations; both the flux-tube model and recent LGT calculations find that the lightest exotic should be a $J^{PC} = 1^{-+}$, albeit with a mass of $\approx 1.9 - 2.0$ GeV.

Since $q\bar{q}g$ hybrids span flavor nonets, there will be many more such states if this is indeed a correct interpretation of the data. Specific models of hybrids such as the flux-tube model and the bag model anticipate that there should be hybrid
flavor nonets with all $J^{PC}$, the majority having nonexotic quantum numbers. In the flux tube model the lightest hybrid multiplet includes the nonexotic states

$$J^{PC} (\text{flux - tube hybrid nonexotics }) = 0^{-+}, 1^{--}, 1^{++}, 2^{++}$$  \hspace{1cm} (1)

and in the bag model the lightest hybrid multiplet includes

$$J^{PC} (\text{bag - model hybrid nonexotics }) = 0^{-+}, 1^{--}, 2^{--}.$$  \hspace{1cm} (2)

In addition to hybrids we also expect glueball degrees of freedom, which will overpopulate the $I=0$ sector relative to expectations for $q\bar{q}$. The spectrum of “quenched” glueballs (in the absence of quarks) is reasonably well established from LGT studies \[8\]; the lightest state is a scalar at about 1.6 GeV, followed by a $0^{-+}$ and a $2^{++}$ at about 2.2-2.3 GeV. The scalar glueball has been speculatively identified with the $f_0(1500)$ \[9\] or alternatively the $f_0(1710)$, \[10\] and especially in the $f_0(1500)$ case one needs to invoke important $n\bar{n} \leftrightarrow G \leftrightarrow s\bar{s}$ mixing to explain the observed decay branching fractions.

Finally, there is a spectrum of weakly bound molecular states analogous to the $K\bar{K}$ molecule candidates \[11\] $f_0(980)$ and $a_0(980)$, which is at least as extensive as the Nuclear Data Sheets. Unlike glueballs, the spectrum of molecular states beyond $K\bar{K}$ and the nuclei and hypernuclei has received little theoretical attention. There are some quark-model calculations that indicate that vector meson pairs may bind \[12\] but there has been no systematic investigation of the expected spectrum.

As a background to these various hadron exotica we have a spectrum of conventional $q\bar{q}$ states, which must be identified if we are to isolate non-$q\bar{q}$ exotica. Since the lightest non-$q\bar{q}$ states typically have masses and quantum numbers which are expected for radially excited $q\bar{q}$ states, it is especially important to identify radial excitations.

Identification of the $q\bar{q}$ and non-$q\bar{q}$ states in the spectrum will require that we clarify meson spectroscopy to masses of at least 2.5 GeV, so that the pattern of glueballs, hybrids and multiquarks can be established through the identification of sufficient examples of each type of state.

2 States reported in the WHS99 “Radial Excitations” session

2.1 $p\bar{p}$ annihilation in flight

In this session we heard new results from Crystal Barrel $p\bar{p}$ annihilation data in flight, as analyzed by D.Bugg and collaborators \[13\], in several final states. The final states
Table 1: I=0 states reported in Crystal Barrel data in p\bar{p} → PsPs and ηπ^0π^0 by Bugg et al.

| J^PC | M(MeV)      | Γ(MeV)     | comments     |
|------|-------------|------------|--------------|
| 6++  | 2530(40)    | 250(60)    | weak ππ      |
| 4++  | 2335(20)    | 150(35)    |              |
| 4++  | 2025(15)    | 180(15)    |              |
| 3++  | 2280(30)    | 210(30)    | ηπ^0π^0      |
| 3++  | 2000(40)    | 250(40)    | "            |
| 2++  | 2365(30)    | 300(50)    | ππ            |
| 2++  | 2240(40)    | 170(50)    | ηπ^0π^0      |
| 2++  | 2210(40)    | 310(45)    | ηπ^0π^0      |
| 2++  | 2065(30)    | 225(30)    | ηπ^0π^0      |
| 2++  | 1945(30)    | 220(40)    | "            |
| 2−+  | 2300(40)    | 270(40)    | ηπ^0π^0      |
| 2−+  | 2040(40)    | 190(40)    | "            |
| 1++  | 2340(40)    | 340(40)    | ηπ^0π^0      |
| 0++  | 2335(25)    | 225(40)    | very weak ππ |
| 0++  | 2095(10)    | 190(12)    |              |

discussed were ππ, ηη, ηη', 3π^0, ηπ^0, η'π^0 and ηπ^0π^0. Some very interesting results were reported, which will allow us to quote some new estimates for the masses of previously unknown higher-mass n\bar{n} quarkonium multiplets.

The I=0 states reported by Bugg in π^+π^−, π^0π^0, ηη, ηη' and ηπ^0π^0 (taken from a recent preprint [4]) are summarized in Table 1. Bugg also reported results for I=1 states seen in π^+π^−, 3π^0, ηπ^0 and η'π^0, given in Table 2.

If these results are confirmed, they represent a considerable contribution to the determination of the n\bar{n} quarkonium spectrum in the mass region of 1.9-2.5 GeV, which is especially relevant to searches for glueballs and excited hybrids.

2.2 τ hadronic decays at CLEO: the a_1(1700)

In addition to evidence for radially excited states in p\bar{p} annihilation, we also heard results from R.Baker [5] about the possible evidence for a radial excitation, the a_1(1700), in τ hadronic decays. The process discussed was τ^− → ν_τπ^−π^0π^0; this is dominated by ρπ, which originates primarily from the a_1(1260). Since the a_1(1260) appears clearly here, one might expect to see the radial excitation a_1(1700) as well. This state is interesting as a benchmark for the 2P n\bar{n} multiplet, and in view of the reported exotic π_1(1600) nearby in mass we must be especially careful in identifying 2P q\bar{q} states; nonexotic hybrids with 1^{++} are predicted by the flux-tube model to
Table 2: $I=1$ states reported in Crystal Barrel data in $p\bar{p} \to \pi^+\pi^-$, $3\pi^0$, $\eta\pi^0$ and $\eta'\pi^0$ by Bugg et al.

| $J^P C$ | $M$(MeV)   | $\Gamma$(MeV) | comments     |
|--------|------------|---------------|--------------|
| 5$^-$  | 2335(20)   | 150(35)       | $\pi^+\pi^-$ |
| 4$^{++}$ | 2280(20)   | 205(25)       |              |
| 4$^{++}$ | 2015(25)   | 305(80)       |              |
| 3$^{++}$ | 2310(40)   | 180$^{+20}_{-60}$ |       |
| 3$^{++}$ | 2070(20)   | 170(40)       |              |
| 3$^{-}$  | 2215(35)   | 340(55)       | $\pi^+\pi^-$ |
| 3$^{--}$ | 1950(15)   | 150(25)       | "           |
| 2$^{++}$ | 2270(30)   | 260(50)       |              |
| 2$^{++}$ | 2080(20)   | 235(45)       |              |
| 2$^{++}$ | 1990(30)   | 190(50)       |              |
| 1$^{++}$ | 2100(20)   | 300$^{+30}_{-60}$ |       |
| 1$^{++}$ | 2340(40)   | 230(70)       |              |
| 1$^{-}$  | 2270(60)   | 260(65)       | $\pi^+\pi^-$ |
| 1$^{--}$ | 2015(45)   | 270(115)      | "           |
| 0$^{++}$ | 2025(30)   | 330(75)       |              |

belong to the same first hybrid multiplet. The quark model $I=1$ $2^3P_1$ $q\bar{q}$ state is predicted to have a “fingerprint” decay amplitude; the leading mode, $\rho\pi$, is predicted to be dominantly D-wave \cite{16,17}. The S-wave is allowed, but has a node near the physical point due to the radially excited wavefunction. This dramatic prediction was apparently confirmed by earlier VES results \cite{18} and by E852 at BNL as reported by Ostrovidov \cite{3}, but apparently not by recent VES results \cite{2} (this analysis however is still in progress).

The $a_1(1700)$ may appear as a broadening of the $a_1(1260)$ shoulder at high mass in $\tau$ decays; the reported $a_1(1260)$ width of $\sim 600 – 800$ MeV is much larger than the width observed at E852, and may indicate the presence of additional states. Separation of the S- and D-wave $\rho\pi$ amplitudes may be crucial in identifying the $a_1(1700)$; this was certainly the case for E852.

We note in passing that this state was discussed in $\tau$ hadronic decays in other sessions by Kravchenko \cite{19} (CLEO) and McNulty \cite{20} (Delphi); both reported improved fits with an $a_1(1700)$, but due to the dominant $a_1(1260)$ signal the $a_1(1700)$ could not be identified with confidence. The $a_1(1700)$ may also have been seen in $\tau$ decays to $\eta\pi\pi\pi$, in the $f_1\pi$ final state. In $f_1\pi$ a clear peak does appear at the correct mass \cite{21}, but there is a concern that the limited $\tau$ phase space has truncated the resonance shape. Since the expected branching fractions of the $a_1(1700)$ are
Table 3: Possible radial excitations reported in other WHS99 sessions.

| $J^{PC}$ | $M$(MeV) | $\Gamma$(MeV) | mode | contribution |
|----------|----------|---------------|------|--------------|
| $I=0$:   |          |               |      |              |
| $4^{++}$ | 2330(30) | 290(70)       | $\eta\pi^+\pi^-$ | Dorofeev (VES) |
| $4^{++}$ | 2330(20) | 240(40)       | $\omega\omega$   | Dorofeev (VES) |
| $2^{++}$ | 2310(30) | 230(80)       | $\eta\pi^+\pi^-$ | Dorofeev (VES) |
| $2^{++}$ | 2130(35) | 270(50)       | $K^+K^-$         | Kirk (WA102)  |
| $2^{++}$ | 1980(50) | 450(100)      | $\eta$           | Peters (CBar) |
| $2^{++}$ | 1945(45) | 130(70)       | $\eta$           | Kondashov (GAMS) |
| $2^{++}$ | 1940(10) | 150(20)       | $\omega\omega$   | Dorofeev (VES) |
| $2^{++}$ | $\approx$ 1645(20) | $\approx$ 200(30) | $\pi^0\pi^0, \eta\eta$ | Peters (CBar) |
| $2^{++}$ | 1645(35) | 230(120)      | $\eta\eta$       | Kondashov (GAMS) |
| $0^{++}$ | 1980(30) | 190(40)       | $\pi^0\pi^0, \eta\eta$ | Kondashov (GAMS) |
| $I=1$:   |          |               |      |              |
| $3^{--}$ | 2300(50) | 240(60)       | $\eta\pi^+\pi^-$ | Dorofeev (VES) |
| $3^{--}$ | 2180(40) | 260(50)       | $\eta\pi^+\pi^-$ | Dorofeev (VES) |
| $2^{++}$ | 1752(21)(4) | 150(110)(34) | $\gamma\gamma \rightarrow \pi^+\pi^-\pi^0$ | Braccini (L3) |
| $2^{++}$ | $\approx$ 1670(20) | $\approx$ 280(70) | $\eta\pi^0$ | Peters (CBar) |
| $1^{--}$ | [PDG]    | [PDG]         | $\rho\eta$       | Dorofeev (VES) |
| $1^{--}$ | 1450 [PDG] | [PDG]        | $\rho\eta$       | Dorofeev (VES) |
| $0^{--}$ | 1400(40) | 275(50)       | $\rho\pi$        | Thoma (CBar)  |

known, \cite{7} and have been measured by E852, it should be straightforward to test the strength of the possible $a_1(1700)$ peak in $f_1\pi$ at CLEO.

3 Possible radial excitations reported in other WHS99 sessions

Many states were reported in talks in other WHS99 sessions which are plausible candidates for radial excitations. Since these talks will be reviewed by the appropriate session chairs I will not discuss them in general in any detail here, but instead simply quote the quantum numbers, mass, width, author of the talk and the experiment (Table 3). Where these are especially interesting for the subject of radial excitations I will discuss the particular state subsequently.

4 Theoretical aspects of identifying quarkonia and non-quarkonia

4.1 Masses

One might wonder how any of these levels can be confidently identified as quarkonia, since many non-$q\bar{q}$ states with the same quantum numbers are expected.
Table 4: *Suggested multiplets of radially excited n\bar{n} states*

| nL  | M (GeV) | representative WHS99 candidates                        |
|-----|---------|--------------------------------------------------------|
| 2S  | 1.4     | \(\rho(1450), \pi(1300)\)                             |
| 3S  | 1.8     | \(\pi(1740)\)                                        |
| 4S  | 2.1     | \(\rho(2150)\)                                       |
| 2P  | 1.7     | \(f_2(1650), a_2(1700), a_1(1700)\)                   |
| 3P  | 2.08    | \(f_0(2095), a_1(2100), a_0(2050)\)                   |
| 4P  | 2.34    | \(f_0(2335), a_1(2340)\)                             |
| 2D  | 2.0     | \(\omega_3(1950), \eta_2(2040)\)                     |
| 3D  | 2.3     | \(\rho_3(2300), \omega_3(2215), \eta_3(2300)\)       |
| 2F  | 2.29    | \(f_4(2290), f_3(2280), a_4(2280), a_3(2310)\)       |

For the present, masses are our best guide. Fortunately, as one increases the angular momentum of the \(q\bar{q}\) pair, the multiplet splittings (spin-spin, spin-orbit, tensor) decrease rapidly. This is because these are short-distance effects (in the usual OGE and linear confinement picture), and the centrifical barrier suppresses the short-distance part of the \(q\bar{q}\) wavefunction.

For the lowest-mass multiplet of given \(L_{q\bar{q}}\), one can usually identify the maximum-J state, which is frequently relatively narrow and gives rapidly varying angular distributions. For example, in the Bugg *et al* results (Tables 1 and 2) the maximum-J states in the lowest-lying \(L_{q\bar{q}} = 3, 4\) and 5 multiplets are presumably represented by the \(f_6(2530), \rho_5(2335)\) and \(f_4(2025)\). These are all well-established PDG states [22]. Given these levels, we expect the other \(n\bar{n}\) members of these \(1H(2.55), 1G(2.35)\) and \(1F(2.05)\) multiplets (here rounded to 50 MeV) nearby in mass.

Inspection of the tables of states reported in \(p\bar{p}\) (Tables 1 and 2) and the higher-mass states reported in other sessions (Table 3) suggests masses for some radially-excited \(q\bar{q}\) multiplets, which we list in Table 4 and display in Figure 1. The table includes representative candidates discussed in contributions to WHS99. Note that these multiplets are rather lighter than expected by Godfrey and Isgur [23], who quoted \(n\bar{n}\) masses for radial multiplets up to 3S, 2P and 2D; their results are

\[
M(3S)_{|\text{GI}} = 1.88 \text{ GeV} (\pi), 2.00 \text{ GeV} (\rho),
\]

\[
M(2P)_{|\text{GI}} \approx 1.80 \text{ GeV},
\]

\[
M(2D)_{|\text{GI}} \approx 2.14 \text{ GeV}.
\]

Comparison with Table 4 shows that experiment is apparently finding these \(n\bar{n}\) radial excitations about 0.1-0.2 GeV lower in mass than Godfrey and Isgur anticipated. For
Figure 1: Radially-excited $n\bar{n}$ multiplet levels suggested by recent data (see Table 4).

numerical estimates of expected masses of radially excited levels one can of course use “mass systematics” such as the radial Regge trajectories discussed by Bugg \cite{13} and Peaslee \cite{24}. Decay calculations and other matrix elements however require explicit meson wavefunctions, which are usually determined in a Godfrey-Isgur type model.

4.2 Strong Decays

It will be very interesting to see if these new, rather low-mass candidates for radially excited $q\bar{q}$ levels can still be accommodated in a Coulomb plus linear potential model, or if there appears to be serious disagreement with this very widely used description of meson spectroscopy.

In addition to masses and quantum numbers, we can expect to have experimental data on some relative strong branching fractions. These can be very valuable indicators of the nature of a hadron; examples include the evidence that $\phi = s\bar{s}$ (a weak $\rho\pi$ mode), $f_2(1525) = s\bar{s}$ (a weak $\pi\pi$ mode), and that $\psi(3097) = c\bar{c}$ (weak light hadron modes generally). Similarly, discussions of the nature of the scalar states $f_0(1500)$ and $f_0(1710)$ have centered on explanations of their strong branching fractions to $\pi\pi, K\bar{K}, \eta\eta$ and $\eta\eta'$. (Here the situation is more complicated because the
Table 5: Theoretical two-body partial widths (MeV) of a $\pi(1800)$

| $\pi(1800)$ | $\rho\pi$ | $\rho\omega$ | $\rho(1465)\pi$ | $f_0(1300)\pi$ | $f_2\pi$ | $K^*K$ | total |
|-------------|-----------|--------------|-----------------|----------------|---------|-------|-------|
| thy. $\frac{11}{2}$ (q\bar{q}) | 31        | 73           | 53              | 7              | 28      | 36    | 228   |
| thy. $\frac{27}{2}$ (hybrid)   | 30        | 0            | 30              | 170            | 6       | 5     | $\approx 240$ |

Theoretical understanding of glueball strong decays is not yet well developed.)

For quarkonia there are two commonly used strong decay models, known as the flux-tube model and the $^3P_0$ model. These are rather similar, in that the assumed decay mechanism in both cases is production of a $q\bar{q}$ pair from the vacuum with $^3P_0$ (vacuum) quantum numbers; this mediates the dominant $(Q\bar{Q}) \to (Q\bar{q})(q\bar{Q})$ strong decay process. This mechanism is actually poorly understood and is presumably a nonperturbative effect; the perturbative OGE pair production amplitude is found in explicit quark model calculations to be numerically rather weak in most channels 25).

Theorists have carried out detailed decay calculations of higher-mass $q\bar{q}$ states, including all open two-body modes, for $n\bar{n}$ states up to 2.1 GeV 17), and for a few specific cases at higher mass 26). If these predictions are reasonably accurate they will be very useful in distinguishing relatively pure $q\bar{q}$ states from glueballs, hybrids or molecules. As specific examples, Tables 5 and 6 compare the partial widths expected for quasi-two-body modes of $^3S_0\pi(1800)$ $q\bar{q}$ and $^2S_1a_1(1700)$ $q\bar{q}$ states 17) to expectations for flux-tube hybrids at the same mass. 27) Evidently the study of a few characteristic modes, here $\rho\omega$ and $f_0(1300)\pi$, can distinguish these assignments. Of course we would prefer to know as many branching fractions as is experimentally feasible, because the physics may be more complicated than these simple decay models assume. In the $\pi(1800)$ case the presence of a strong $\rho\omega$ mode was reported in this meeting by VES 2), which argues against this bump being due to a single flux-tube hybrid. The earlier reports of a large $f_0(1300)\pi$ mode argue against a simple $q\bar{q}$ assignment. More than one state may be present, and in the most complicated case these basis states may be strongly mixed.

One should note that we still have little information regarding the accuracy of our strong decay models for higher-mass states, and more quantitative information

Table 6: Theoretical two-body partial widths (MeV) of an $a_1(1700)$

| $a_1(1700)$ | $\rho\pi$ | $\rho\omega$ | $b_1\pi$ | $\rho(1465)\pi$ | $f_0(1300)\pi$ | $f_1\pi$ | $f_2\pi$ | $K^*K$ | total |
|-------------|-----------|--------------|----------|-----------------|----------------|---------|---------|-------|-------|
| thy. $\frac{11}{2}$ (q\bar{q}) | 58        | 15           | 41       | 41              | 2              | 18      | 39      | 33    | 246   |
| thy. $\frac{27}{2}$ (hybrid)   | 30        | 0            | 110      | 0               | 6              | 60      | 70      | 20    | $\approx 300$ |

...
on branching fractions from well-established $q\bar{q}$ states is badly needed to allow tests of the decay models. One of the few states discussed at WHS99 for which information on relative mode strengths was reported was in the VES observation of the $a_4(2040)$. Although this is not a radial excitation, these data show how detailed comparisons with theoretical branching fractions for radials may be possible in future. The relative branching fractions of the $a_4(2040)$ to $f_2\pi$, $\rho\pi$ and $\rho\omega$ were reported, which we compare to the predictions of the $^3P_0$ model [17] in Table 7. (Only modes with theoretical partial widths $> 5$ MeV are tabulated in Table 7; for the complete set see Barnes et al. [17].) Evidently there is good agreement at present accuracy, which is a nontrivial test of the model since these modes represent different angular decay amplitudes.

Unfortunately there have been few attempts to measure relative branching fractions of higher-mass states, and none were reported for the candidate radial excitations discussed here. This is an extremely important topic for future experimental studies.

5 The Future of Radials

Future work on higher-mass $q\bar{q}$ spectroscopy will hopefully establish the masses of missing states in the known multiplets (especially those with masses and quantum numbers expected for glueballs and hybrids), identify the higher-mass states to a mass of at least $\sim 2.5$ GeV, and determine most branching fractions and decay amplitudes of a subset of these states in sufficient detail to be useful to theorists.

Certain $q\bar{q}$ multiplets are especially interesting because their $J^{PC}$ quantum numbers and masses are similar to expectations to glueballs and hybrids; the $q\bar{q}$ levels either form a background and must be identified and eliminated as potential exotica, or they may mix strongly with the glueball or hybrid states so that the relatively pure $q\bar{q}$ level does not exist in nature. Since we cannot say a priori which possibility is correct, it is especially important to clarify the experimental spectrum in these mass regions. Multiplets of special interest for this reason are:

| $a_4(2040)$ | $\eta\pi$ | $\rho\pi$ | $\rho\omega$ | $b_1\pi$ | $f_2\pi$ | $KK$ | $K^*K^*$ |
|-------------|---------|---------|--------|--------|-------|------|---------|
| thy. [17] ($q\bar{q}$) | 12 MeV | 33 MeV | 54 MeV | 20 MeV | 10 MeV | 8 MeV | 9 MeV |
| expt. [4] | - | $\equiv 1$ | 1.5(4) | - | 0.5(2) | - | - |
Table 8: *Theoretical two-body partial widths (MeV) of a $2^3P_2 f_2(1700) q\bar{q}$*

| $f_2(1700)$ | $\pi\pi$ | $\eta\eta$ | $\eta'/\eta$ | $\rho\rho$ | $\omega\omega$ | $\pi_{2S}\pi$ | $a_1\pi$ | $a_2\pi$ | $KK$ | $K^*K$ | total |
|-----------|---------|-----------|-------------|----------|------------|-------------|---------|---------|------|------|------|
| thy. [27] | 81 | 4 | 1 | 159 | 56 | 8 | 16 | 43 | 20 | 17 | 405 |

Table 9: *Theoretical two-body partial widths (MeV) of a $2^3P_2 a_2(1700) q\bar{q}$*

| $a_2(1700)$ | $\eta\pi$ | $\eta'\pi$ | $\rho\pi$ | $\rho\omega$ | $\eta_{2S}\pi$ | $\rho_{2S}\pi$ | $b_1\pi$ | $f_1\pi$ | $f_2\pi$ | $KK$ | $K^*K$ | total |
|-------------|---------|-----------|----------|------------|-------------|-------------|---------|---------|------|------|------|------|
| thy. [27]   | 23 | 10 | 104 | 109 | 3 | 0 | 28 | 4 | 20 | 20 | 17 | 336 |

• $2P$

The clarification of the $2P$ multiplet is a high-priority topic; if the reported exotic $\pi_1(1600)$ is a hybrid, nonexotic hybrid partners should appear at a similar mass. We should therefore find an overpopulation of states in this mass region, and perhaps anomalous decay branching fractions if there is strong quarkonium-hybrid mixing. The flux-tube model expects exotic partners with $J^{PC} = 0^{+-}$ and $2^{+-}$, and nonexotics with $J^{PC} = 0^{-+}, 1^{+-}, 1^{--}, 1^{++}$ and $2^{-+}$, all at about the same mass as the $1^{-+}$. Thus we expect an apparent duplication of the $2^1P_1$ and $2^3P_1$ $2P$ quarkonium levels by hybrids at similar masses.

Expected branching fractions for flux-tube hybrids have been calculated in detail by Close and Page [27], and these modes should be studied for evidence of both hybrid and quarkonium parent resonances.

Studies of $2P$ candidates that are not expected to have nearby hybrids are important as calibration studies for the decay models. The $2^3P_2$ states $a_2(1670 – 1750)$ and $f_2(1645)$ reported at this meeting may be most straightforward to study, since neither hybrids nor glueballs are expected in $2^{++}$ at this mass. The theoretical partial widths for $2^3P_2$ $f_2(1700)$ and $a_2(1700)$ quarkonia are given in Tables 8 and 9. Although the $f_2(1700)$ state is reported in $\pi^0\pi^0$ and $\eta\eta$ and the Crystal Barrel reports the $a_2(1700)$ in $\eta\pi^0$, these modes are not predicted to be dominant; for $f_2(1700)$ $\rho\rho$ is expected to be largest, and an experimentally clean $\omega\omega$ mode with $1/3$ the $\rho\rho$ strength is also predicted. Similarly the $a_2(1700)$ should have a large $\rho\omega$

Table 10: *Theoretical decay amplitudes (GeV$^{-1/2}$) for $f_2(1700) \to \omega\omega$*

| $f_2(1700)$ | $^5S_2$ | $^1D_2$ | $^5D_2$ | $^5G_2$ |
|-------------|---------|---------|---------|---------|
| thy. [27]   | (q\bar{q}) | +0.34 | -0.031 | +0.082 | 0 |
These $VV$ modes are quite interesting in that there are several subamplitudes, and the predicted amplitude ratios are nontrivial. As an example, the numerical $^3P_0$ decay amplitudes for $f_2(1700) \rightarrow \omega\omega$ are given in Table 10. If the S-wave and D-wave $\omega\omega$ amplitudes from this state could be separated and compared, we would have a very sensitive test of the decay model, and if there is agreement we could apply the same model with more confidence to the decays of other candidate high-mass $q\bar{q}$ states.

As a final observation, the report by Braccini (L3 Collaboration) of a $2P$ candidate $a_2(1750)$ in $\gamma\gamma$ collisions is especially interesting because this is the first radial excitation to be reported in $\gamma\gamma$. Theoretically, radially excited $q\bar{q}$ states should appear with little suppression in $\gamma\gamma$ collisions, but to date only this radial candidate has been reported. There may actually be a problem here, as the mass reported for an excited $a_2$ state by Crystal Barrel, $\approx 1670(20)\text{ MeV}$, does not appear consistent with the L3 mass.

- $3P$ and $4P$

These multiplets, which experimentally lie at about 2.08 GeV and 2.34 GeV (for $n\bar{n}$; see Table 4), will be of interest because of the presence of the lightest tensor glueball. Of course there will be hybrids in this region as well, so we can expect a complicated spectrum of overlapping resonances. At present there is no theoretical guidance regarding decay modes of these $q\bar{q}$ states; such a study would be difficult to motivate without evidence (for example from the $2P$ multiplet) that the decay models will give useful results for these high radial excitations.

- $2S$ and $3S$

The $2S$ and $3S$ multiplets are also interesting due to their proximity to the reported hybrid candidates $\pi_1(1405)$ and $\pi_1(1600)$; both the bag model and flux-tube model predict that the lightest $1^{--}$ hybrid has $0^{++}$ and $1^{--}$ partners nearby in mass. These should be observable as an overpopulation of states in the $L_{q\bar{q}} = 0$ $q\bar{q}$ sectors.

The $2S$ multiplet has historically been problematic because there are broad overlapping states in the $1^{--}$ sector; at least two states near 1.45 and 1.7 GeV are needed to explain the data (notably $e^+e^- \rightarrow \pi\pi$ and $\omega\pi$). The observation of the $\rho(1450)$ in $\tau$ decays at CLEO was reported here by Kravchenko, who also noted the absence of a $K^*(1410)$ signal in $K\pi$. The topic of vector meson spectroscopy in this mass region was recently reviewed by Donnachie and Kalashnikova, who concluded that an additional vector was required in both $I=0$ and $I=1$ channels to fit
the data. In I=1, the weakness of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ relative to $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ cannot be explained by the expected $\rho(1700)$ decays alone. This additional state may be the $1^{--}$ vector hybrid, which is expected in both bag and flux-tube models. The recent work on $4\pi$ decays of I=1 vectors by the Crystal Barrel Collaboration has shown that the $a_1\pi$ and $h_1\pi$ modes come from the 1.7 GeV region rather than 1.45 GeV, as expected if the 1.7 GeV state is the 1D $q\bar{q}$ state and the 1.45 GeV is 2S, which is the usual quark model assignment. Clearly a more detailed study of the different $4\pi$ charge states would be enlightening.

In the $2^1S_0$ states, the decay of the $\pi(1300)$ is observed by Crystal Barrel to be dominantly $\rho\pi$ rather than $(\pi\pi)_S\pi$, which is in agreement with the expectations of the $^3P_0$ model. Of course the $\pi(1800)$ state has attracted considerable attention as a possible hybrid, largely because of the $f_0(1300)\pi$ decay mode (see Table 5). The VES report of a large $\rho\omega$ mode at about 1.74 GeV was attributed by Dorofeev to an overpopulation of $\pi(1740-1800)$ states, and we should presumably identify the 3S quark model state identified with the large $\rho\omega$ signal. This can be tested by studies of $f_2\pi$ and $K^*K$; a $3^1S_0$ $q\bar{q}$ $\pi(1800)$ is predicted to have branching fractions into these modes about half as large as its $\rho\omega$ branching fraction (see Table 5).

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