RADIAL EXCITATIONS*

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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 [1, 2, 3] 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 [1, 4, 5]. 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 [6] and recent LGT calculations [7] 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

Table 1: *I=0 states reported in Crystal Barrel data in* $p\bar{p} \to PsPs$ and $\eta\pi^o\pi^o$ *by Bugg et al.*

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

discussed were $\pi\pi$, $\eta\eta$, $\eta\eta'$, $3\pi^o$, $\eta\pi^o$, $\eta'\pi^o$ and $\eta\pi^o\pi^o$. 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 $\pi^+\pi^-$, $\pi^o\pi^o$, $\eta\eta$, $\eta\eta'$ and $\eta\pi^o\pi^o$ (taken from a recent preprint [14]) are summarized in Table 1. Bugg also reported results for I=1 states seen in $\pi^+\pi^-$, $3\pi^o$, $\eta\pi^o$ and $\eta'\pi^o$, 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 [15] about the possible evidence for a radial excitation, the a_1 (1700), in τ hadronic decays. The process discussed was $\tau^- \to \nu_\tau\pi^-\pi^o\pi^o$; this is dominated by $\rho\pi$, 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 $\pi_1(1600)$ 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 3: *Possible radial excitations reported in other WHS99 sessions.*

J^{PC}	M(MeV)	Γ(MeV)	mode	contribution
I=0:				
4^{++}	2330(30)	290(70)	$\eta\pi^+\pi^-$	Dorofeev (VES)
4^{++}	2330(20)	240(40)	ww	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)	$\eta\eta$	Peters (CBar)
2^{++}	1945(45)	130(70)	$\eta\eta$	Kondashov (GAMS)
2^{++}	1940(10)	150(20)	ww	Dorofeev (VES)
2^{++}	$\approx$ 1645(20)	$\approx$ 200(30)	$\pi^o\pi^o, \eta\eta$	Peters (CBar)
2^{++}	1645(35)	230(120)	$\eta\eta$	Kondashov (GAMS)
0^{++}	1980(30)	190(40)	$\pi^o\pi^o$, $\eta\eta$	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)	$\gamma\gamma \to \pi^+\pi^-\pi^o$	Braccini (L3)
2^{++}	$\approx$ 1670(20)	$\approx$ 280(70)	$\eta\pi^o$	Peters (CBar)
1^{--}	2150 [PDG]	[PDG]	$\rho\eta$	Dorofeev (VES)
1^{--}	1450 [PDG]	[PDG]	$\rho\eta$	Dorofeev (VES)
0^{-+}	1400(40)	275(50)	$\rho\pi$	Thoma (CBar)

known, [17] 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.

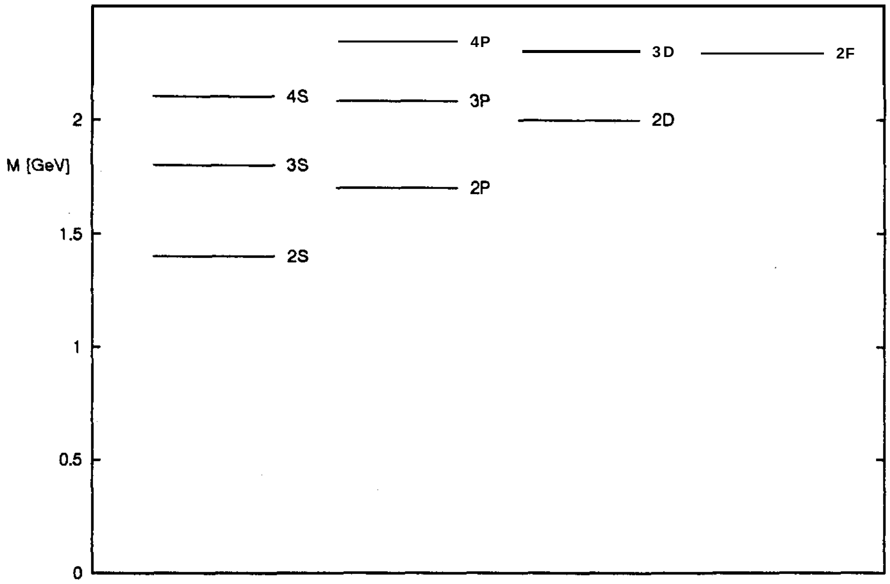

Figure 1: *Radially-excited $n\bar{n}$ multiplet levels suggested by recent data (see Table 4).*

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 [13] and Peaslee[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 7: *Theoretical and observed partial widths of the* $a_4(2040)$

$a_4(2040)$	$\eta\pi$	$\rho\pi$	$\rho\omega$	$b_1\pi$	$f_2\pi$	$K\bar{K}$	$K^*\bar{K}^*$
thy. [17] ($q\bar{q}$)	12 MeV	33 MeV	54 MeV	20 MeV	10 MeV	8 MeV	9 MeV
expt. [2]	-	≡ 1	1.5(4)	-	0.5(2)	-	-

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:

mode. 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) $\to \omega\omega$ are given in Table 10. If the S-wave and D-wave ww 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) [28] 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, [29] 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, [30] $\approx 1670(20)$ 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 $e^+e^- \to \pi\pi$ and $\omega\pi$). The observation of the $\rho(1450)$ in τ decays at CLEO was reported here by Kravchenko [19], 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, [31] who concluded that an additional vector was required in both I=0 and I=1 channels to fit

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