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0^+ Mesons and Glueball Spectroscopy

D.V. BUGG
Queen Mary and Westfield College, London E1 4NS, UK

Abstract

The status of meson spectroscopy is reviewed. Crystal Barrel data on $\bar{p}p$ annhilation at rest identify the whole 0^+ ground-state nonet, plus one extra $I = 0$ state, which may be considered a glueball candidate. Other Crystal Barrel data on $\bar{p}p \to (\eta\pi^0\pi^0)\pi^0$ reveal two new $I = 0$ $J^{PC} = 2^{-+}$ resonances at 1650 and 1850 MeV. Again there are grounds for identifying the latter as a glueball.

Re-analysis of Mark III data on $J/\Psi \to \gamma(4\pi)$ reveals resonances with $J^{PC} = 0^{++}$ at 1505 and 2100 MeV and 2^{++} at 1770 MeV. All have strong or dominant $\sigma\sigma$ decay modes, where σ stands for the $\pi\pi$ S-wave amplitude. There is a remarkable correlation with $\eta\eta$ peaks observed by E760. If glueballs may be identified by dominant decay modes to η, η' and $q\bar{q}$ P-states σ and $f_2(1270)$, a spectrum of seven states emerges between 1440 and 2200 MeV agreeing closely with the cavity model of Jaffe and Johnson, but raised in mass by $\sim$ 550 MeV.

1 The 0^+ Nonet

An important new element in $q\bar{q}$ spectroscopy is the observation by Crystal Barrel of the three states $f_0(1335)$, $a_0(1450)$ and $f_0(1590)$. The first of these is the old $f_0(1400)$. It has been clearly identified in three channels: (a) $\bar{p}p \to (\eta\eta)\pi^0$ [1], Fig. 1, (b) $\bar{p}p \to (\pi^0\pi^0)\pi^0$ [2], and (c) $\bar{p}p \to (\pi^0\pi^0)\eta$ [3]. In $\eta\eta$, it is clearly visible by eye and separated by a dip from $f_0(1505)$. In $3\pi^0$ data, it is hidden beneath $f_2(1270)$, so is not clearly visible be eye, but its presence is demanded by amplitude analysis. In $\eta\pi^0\pi^0$ data, it is right at the top of phase space, so only its lower side is observed. All three channels have been subjected to full amplitude analysis and can be fitted with consistent parameters[4]: $M = 1340 \pm 40$ MeV, $\Gamma = 255^{+60}_{-40}$ MeV. In a fourth channel, $\bar{p}p \to (\pi^+\pi^-\pi^0\pi^0)\pi^0$, it is also seen[5] to decay strongly to $\rho\rho$ (somewhat below threshold) with $M = 1374 \pm 38$ MeV, $\Gamma = 375 \pm 61$ MeV.

The $I = 0$ $a_0(1450)$ was first detected via its $\eta\pi$ decay in the amplitude analysis of $\eta\pi^0\pi^0$ data[3]. It lies close to the $a_2(1320)$ and is broad, $\Gamma = 270 \pm 40$ MeV, so it is again hard to see in the raw data and appears only through amplitude analysis. However, there are now new data where it appears directly[6]. These are on $\bar{p}p \to (K^0_S K^0_S)\pi^0$ and $(K^0_L K^0_L)\pi^0$, Fig. 2. It is visible as a diagonal band across the Dalitz plot and appears strongly in the projection on to $M(K\bar{K})$ at about 1430 MeV.

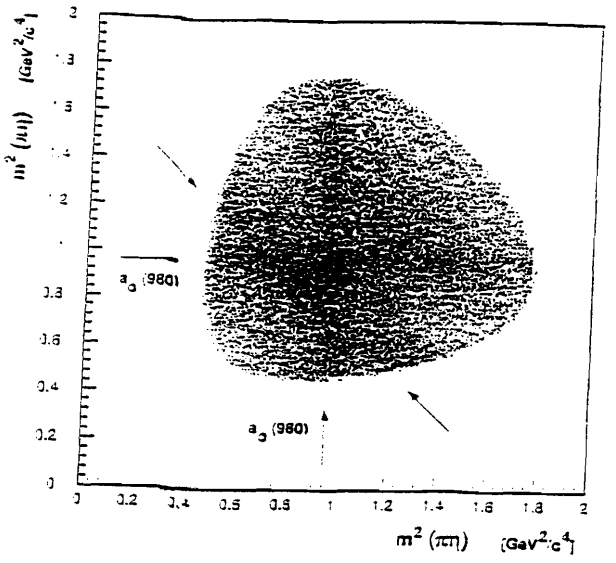

Fig. 1 The Dalitz plot[1] for $\bar{p}p \to (\eta\eta)\pi^0$.Diagonal arrows show $f_0(1505)$.

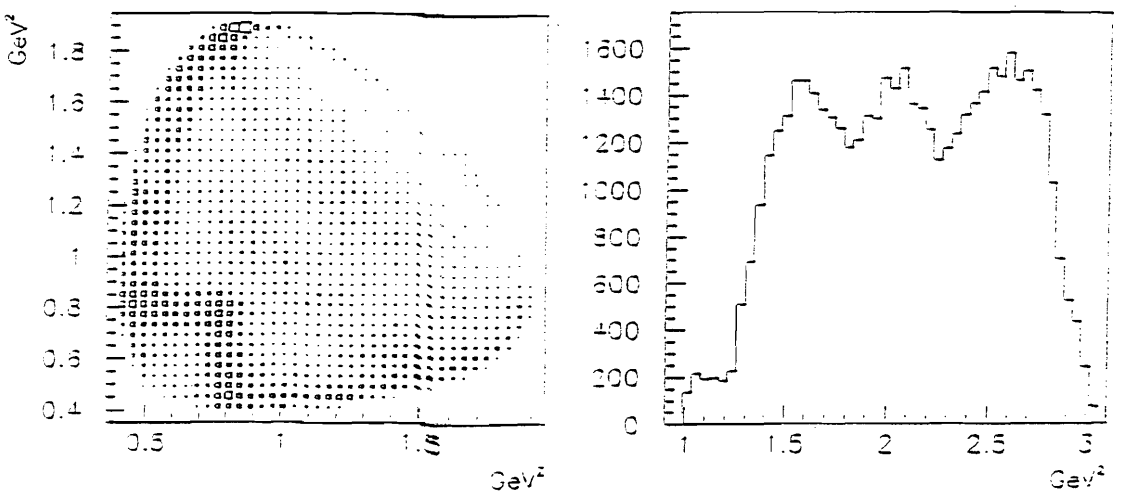

Fig. 2(a) The Dalitz plot for $\bar{p}p \to (K_L^0 K_L^0)\pi^0$ at rest[6]; $M^2(K_L\pi)$ is plotted horizontally and vertically and $M^2(K\bar{K})$ diagonally; (b) the projection on to $M^2(\bar{K}K)$.

These data also have another extremely important feature. The same projection shows an even stronger peak at 1590 MeV. On Fig. 2(a), one sees vertical and horizontal bands due to $K^*(890)$. These bands are enhanced strongly at the bottom left corner of the Dalitz plot. This arises from constructive interference with a diagonal band due to a $K\bar{K}$ resonance at 1590 MeV. Amplitude analysis[6] shows this resonance definitely has $J^P = 0^+$. It is natural to assign it as the $s\bar{s}$ member of the nonet. It

is undoubtedly the state observed earlier at this mass by GAMS and called by them $G(1590)$.

With the well established $K_0^*(1430)$, this completes the $q\bar{q}\ ^3P_0$ nonet. It is somewhat higher in mass than the $^3P_2$, $^3P_1$ and $^1P_1$ nonets. My scheme for the nonets is shown in Table 1. In this scheme, $a_0(980)$, $f_0(975)$ and $f_1(1420)$ are assigned as molecules ($\bar{K}K$ or $\bar{K}K^*$).

Table 1: A scheme for the $q\bar{q}$ states.

State	$I=1$	$I=0$	$s\bar{s}$	$\bar{K}$
$1\ ^3S_1$	$\rho(770)$	$\omega(783)$	$\phi(1020)$	$K^*(892)$
$1\ ^1S_0$	$\pi(140)$	$\eta(548)$	$\eta'(958)$	$K(494)$
$2\ ^3P_2$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$K_2(1430)$
$2\ ^3P_1$	$a_1(1260)$	$f_1(1285)$	$D(1530)$	$K_1(1400)$
$2\ ^3P_0$	$a_0(1450)$	$f_0(1335)$	$G(1590)$	$K_0^*(1430)$
$2\ ^1P_1$	$B(1235)$	$h(1170)$	$h'(1380)$	$K_1(1270)$
$2\ ^3S_1$	$\rho'(1420)$	$\omega'(1390)$	$\phi(1680)$	$K_1^*(1410)$
$2\ ^1S_0$	$\pi'(1300)$	$\eta(1295)$	$\eta(1410)$	$K(1460)$?
$3\ ^3D_3$	$\rho_3(1690)$	$\omega_3(1670)$	$\phi_3(1850)$	$K_3^*(1780)$
$3\ ^3D_2$	missing	missing	missing	$K_2(1816)$
$3\ ^3D_1$	$\rho(1700)$	$\omega(1600)$	missing	$K_1^*(1680)$
$3\ ^1D_2$	$\pi_2(1670)$	$\eta_2(1650)$	missing	$K_2(1773)$
$3\ ^3P_2$	$a_2(1690)$	$f_2(1640)$	$\theta(1720)$??	missing

There is, however, another well established $I=0$ resonance in this mass range, namely $f_0(1505)$. Fig. 3(a) shows the Dalitz plot for Crystal Barrel data at rest on $\bar{p}p \to (\pi^0\pi^0)\pi^0$. This diagram has sixfold symmetry, because of the identical particles in the final state. Let us focus attention on the top corner. There one sees (a) a blob B of events at a mass of 1560 MeV and centred at $\cos\theta = 0$, (b) a band A running across the plot at $M = 1505$ MeV. In the first publication on these data[7], this structure was not fully resolved and the conclusion was drawn that there is a large fraction of P-state annihilation, $\sim 50\%$. The conclusion then was that a 2^- resonance is produced in annihilation from initial $^3P_2$ and $^3P_1$ states. The spin 2 assignment was required to account for the blob (a).

This situation has now changed. Regardless of how much P-state annihilation is fitted to the data, the band at 1505 MeV must have $J^P = 0^+$. This is the vital result, since it establishes a tenth 0^+ state which does not fit into a nonet. It will be shown below that this state appears also in J/ψ radiative decays, the traditional hunting-ground for glueballs.

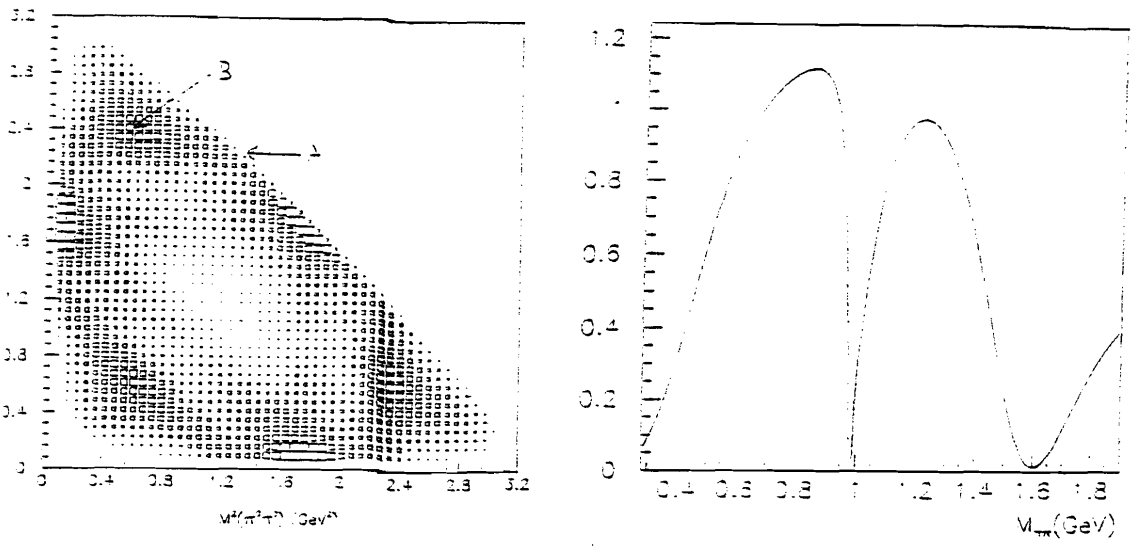

Fig. 3(a) The Dalitz plot[7] for $\bar{p}p \to (\pi^0\pi^0)\pi^0$, (b) the intensity of the $\pi\pi$ S-wave amplitude.

There is still controversy over the explanation of the blob B, depending on how much P-state annihilation is present. My own interpretation is that the annihilation is almost entirely from the initial S-state, for reasons given in a moment. Then the blob arises from constructive interference between two σ bands, where σ stands for the $\pi\pi$ S-wave amplitude. Its intensity is shown in Fig. 3(b). There is a strong, broad peak at 800 MeV, where the phase shift rises slowly through 90°. Peaks at 800 MeV in two channels, say s and t, cross at 1560 MeV in the third, u, channel. This explanation has the virtue that the blob automatically appears at $\cos\theta = 0$. The fitted amplitudes need also to fit two other data sets. Firstly, the Asterix group[8] has published data on $\bar{p}p \to \pi^+\pi^-\pi^0$ with a coincidence with L X-rays; these data correspond to 92% annihilation from initial P-states and are a powerful constraint on what P-state annihilation can be fitted. Secondly, there are data on $\bar{p}n$ (in deuterium) $\to \pi^-\pi^0\pi^0$. These data contain strong $\rho(770)$ signals which act as powerful interferometers and help greatly in constraining the energy dependence of the amplitude in the third $I = 0$ channel. My solution fits all three data sets with a consistent set of parameters, but requires $< 3.5\%$ P-state annihilation in $3\pi^0$. The Mainz group[9] still perseveres with a solution requiring large amounts of P-state annihilation; this has not yet been demonstrated to fit the second and third data sets.

2 Two New $I = 0$ $J^{PC} = 2^{-+}$ Resonances

A state previously missing from Table 1 was the $I = 0$ $^1D_2$ state expected around 1650 MeV as partner to $\pi_2(1670)$. Another reason for being interested in these quantum

numbers is that Jaffe and Johnson[10] have predicted a 2^{-+} glueball at the mean mass of $(TE1)^2$ and $(TM1)^2$ states. If it could be located, it serves as a constraint on the masses of other glueballs. With this motivation, my student Cooper[11] has analysed Crystal Barrel data at 1.94 GeV/c on $\bar{p}p \to (\eta\pi^0\pi^0)\pi^0$.

From this study, he has indeed located two new $I = 0$ 2^{-+} resonances. The first, at 1650 ± 15 MeV, with a width of 180 ± 75 MeV, decays to $a_2(1320)\pi$. It seems a natural candidate for the $q\bar{q}$ partner of $\pi_2(1670)$, whose principle decay mode is to $f_2(1670)\pi$.

The second resonance, at 1850 ± 30 MeV with a width of 225 ± 50 MeV, decays entirely to $f_2(1270)\eta$, as far as we can tell. It appears as a strong signal close to the threshold for this channel, so it is very likely to be produced with $L = 0$ in the final state. A maximum likelihood analysis disfavours strongly $L = 1$ decays for either of these two resonances. One needs to worry whether there could be a single resonance at 1650 MeV, with a high mass tail due to opening of the $f_2(1270)\eta$ channel. The maximum likelihood fit strongly disfavours this possibility when it is tested with a Flatté formula. Such a hypothesis fails to fit the mass dependence of either channel. Furthermore, both resonances have strong, but different interferences with other components of the fit, showing that they must be different resonances.

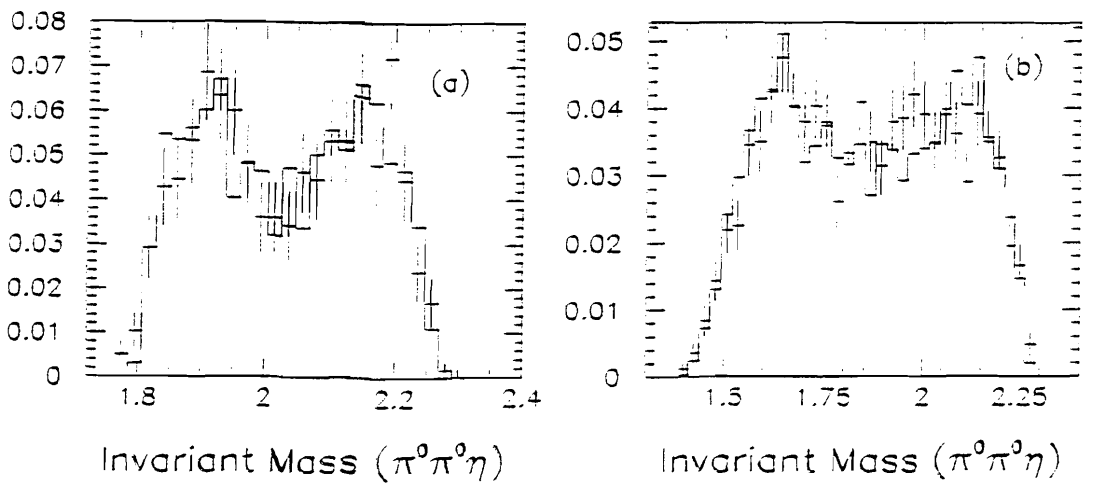

Fig. 4. $M(\eta\pi^0\pi^0)$ distributions from Crystal Barrel data on $\bar{p}p \to (\eta\pi^0\pi^0)\pi^0$ at 1.94 GeV, (a) applying a window around $f_2(1270)$ from 1075 to 1425 MeV, (b) vetoing events with $M(\pi\pi) > 945$ MeV, and selecting events within a window ± 100 MeV around $a_2(1320)$. The histograms show maximum likelihood fits. In (a) the threshold peak is due to $\eta_2(1850) \to f_2(1270)\eta$, and in (b) is due to $\eta_2(1650) \to a_2(1320)\pi$.

Fig. 4 shows some of the evidence for these two resonances. Fig. 4(a) shows $M(\eta\pi\pi)$ when a window is applied to select $f_2(1270)$ and when a second cut rejects events within 100 MeV of $a_2(1320)$. The $\eta_2(1850)$ is clearly visible near threshold, as well as a second resonance near 2150 MeV, attributed to the 2^{++} state observed by

GAMS[12] at 2175 MeV. Fig. 4(b) shows $M(\eta\pi\pi)$ when $f_2(1270)$ and possible $f_0(975)$ contributions are eliminated by vetoing all events where $M(\pi\pi) > 945$ MeV. This figure displays $\eta_2(1650)$ and the higher resonance at 2150 MeV.

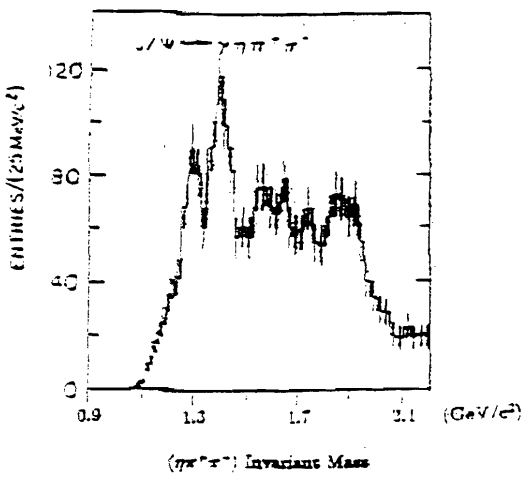

Fig. 5. Mark III data on $J/\Psi \to \gamma(\eta\pi^+\pi^-)$, ref. 13.

What is $\eta_2(1850)$? It is at the right mass for the ninth member of the 2^{-+} nonet. But one expects this state to decay strongly to $\bar{K}K^*$. Secondly, Mark III data[13] on $J/\psi \to \gamma(\eta\pi\pi)$, shown in Fig. 5, have a strong peak at 1850-1875 MeV with a width on its upper side compatible with that seen in Crystal Barrel data. Unfortunately, no J^P analysis has yet been completed at the higher $\eta\pi\pi$ masses. It is tempting to attribute the peaks at 1850 MeV in the two data sets to the same resonance, and hence jump to the conclusion that $\eta_2(1850)$ is the missing 2^{-+} glueball.

3 Resonances in $J/\Psi \to \gamma(4\pi)$

Fig. 6(a) shows E760 data[14] on $\bar{p}p \to (\eta\eta)\pi^0$ at ~ 3.0 GeV. The peaks at $M \simeq$ 1500, 1750 and 2100 MeV show a remarkable similarity to those in Fig. 6(b) in Mark III data[15] on $J/\Psi \to \gamma(\pi^+\pi^-\pi^+\pi^-)$. The DM2 group has also presented very similar data[16] on the latter process. The published analyses of the J/Ψ data have concluded that the three peaks all have $J^P = 0^-$. These quantum numbers are not allowed for identical particles $\eta\eta$.

The coincidence between Figs. 6(a) and (b) has prompted us[17] to look again at the analysis of Mark III data. We noticed that the earlier analyses assumed the final states to be $\rho\rho$. We have tried adding $\sigma\sigma$ final states to the analysis. This gives a considerably improved fit and radically different conclusions about quantum numbers.

The $\rho\rho$ contribution is strong up to 1750 MeV and amounts to $\simeq 50\%$ of the

integrated cross section. We find that the peak near 1500 MeV is due partly to $\iota(1440) \rightarrow \rho\rho$, but partly also to $f_0(1505)$. Fig. 7 shows the best fit omitting $f_0(1505)$. We therefore demonstrate the appearance of $f_0(1505)$ in radiative J/Ψ decays and strengthen the case for interpreting it as a glueball (or a state with a large glueball component).

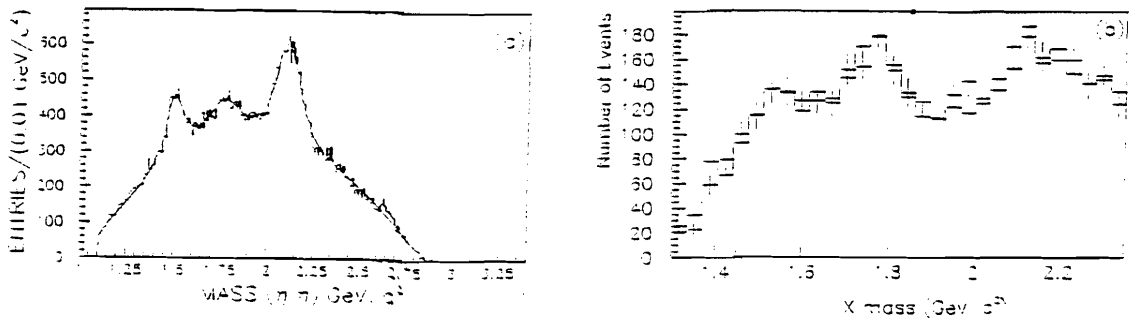

Fig. 6 (a) The $\eta\eta$ mass spectrum from $\bar{p}p \rightarrow \eta\eta\pi^0$ at 3.0 GeV centre of mass energy, ref. 14; (b) the 4π mass spectrum from Mark III data on $J/\Psi \rightarrow \gamma(4\pi)$, ref. 15; crosses are data points and the histogram the fit of ref. 17.

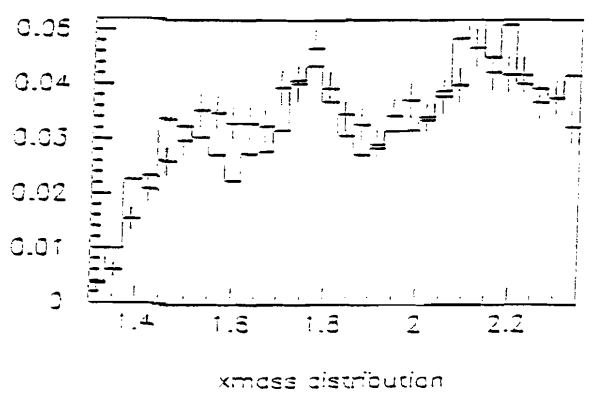

Fig. 7. The best fit to Mark III data omitting $f_0(1505)$.

The resonance at 1770 ± 20 MeV ($\Gamma = 150 \pm 50$ MeV) definitely has $J^P = 2^+$ and

that at 2100 MeV has $J^P = 0^+$. The two 0^+ states decay largely ($\geq 88\%$) to $\sigma\sigma$. The 2^+ state decays 30% to $\sigma\sigma$ with $L = 2$ and 70% to $\rho\rho$ with $L = 0$.

4 A Possible Glueball Spectrum

The 0^+ resonance at 2100 MeV is very striking. It seems hardly plausible that a $q\bar{q}$ radial excitation will be produced so strongly. Some new spectroscopy is required.

The appearance of these three resonances in both J/Ψ radiative decays and $\eta\eta$ is strongly suggestive of glueballs. Gerstein, Likhoded and Prokoshkin[18] have argued that states decaying to $\eta\eta$ and $\eta\eta'$ are likely glueball candidates. In Fig. 8, further states decaying to η and η' are collected. There is a remarkable similarity to the spectrum proposed by Jaffe and Johnson[10] in a cavity model, although all states lie $\simeq 550$ MeV higher than they predicted. The 2^{-+} and 1^{-+} states lie close to the centre of gravity of $(TE1)^2$ and $(TM1)^2$, 1890 MeV, as predicted. The 0^{-+} state, $\iota(1440)$ lies much lower, suggesting strong mixing with η and η' and their radial excitations; the anomalous $\bar{K}K^*$ decay modes of $\iota(1440)$ may well be due to mixing with the $s\bar{s}$ component of the radial excitation.

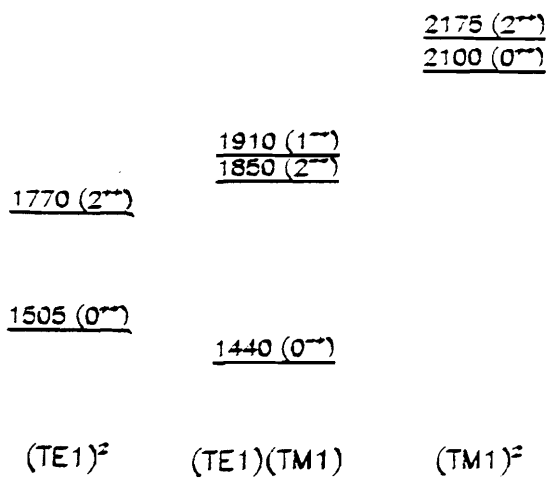

Fig. 8. A suggested spectrum for the lowest seven glueball states.

All the states of Fig. 8 have properties which make them difficult to fit into $q\bar{q}$ spectroscopy in a simple way. For example, $f_0(1505)$, $f_0(2100)$ and $f_2(2175)$ are not seen in $K\bar{K}$ decays, so they cannot easily be accomodated as $s\bar{s}$ states. The fact that the E760 group sees $f_0(1505)$ in $\eta\eta$ but not $G(1590)$ suggests that their peaks are not an $s\bar{s}$ spectrum. Yet it is distinct from the spectrum seen in $\pi\pi$; I interpret the latter as due to towers of $q\bar{q}$ states.

The 1^{-+} state at 1910 MeV does not have well established J^P. The GAMS group points out that its branching ratio to $\eta\eta$ is at least a factor 30 less than to $\eta\eta'$

and therefore suggest $J^P = 1^-$ or 3^-. It is important to check this experimentally with higher statistics. For reasons given below, an alternative decay mode should be $f_1(1285)\eta$. Several theorists[19,20] have argued that 1^{-+} is forbidden for glueballs made of massless gluons. If they are right, massive gluons would be required if the 1910 MeV state is confirmed. This point is one theorists should now re-examine.

The difference in mass between the states of Fig. 8 and the prediction of Jaffe and Johnson is intriguing, e.g. $f_0(1505)$ compared with a prediction of 960 MeV. Their arithmetic goes essentially as follows. Quarks are nearly massless. In a cavity, they acquire a zero-point energy corresponding to fitting the wave function into the cavity. Suppose the cavity radius for glueballs and $q\bar{q}$ states is the same; this is hard to avoid because of mixing. The boundary conditions for gluonic wave functions requires a momentum 2.74/2.04 times higher than for $q\bar{q}$, hence the prediction of $\sim$ 960 MeV for the $(TE1)^2$ state. Raising the glueball state by $\sim 550 MeV$ requires a gluon mass $\simeq (750^2 - 480^2)^{1/2} \simeq 580$ MeV. Similar arithmetic for $f_0(2100)$ gives a gluon mass $\simeq 680 MeV$. This arithmetic cannot be expected to be precise, since it is likely that both $f_0(1505)$ and $f_0(2100)$ mix to some extent with nearby $q\bar{q}$ states, and their masses will be affected. Also a simple cavity is obviously an approximation.

The $f_2(1770)$ state may be the same as $f_2(1810)$ observed by GAMS[21] in 4π final states and the same as the $\eta\eta$ state[22] they see at 1744 ± 15 MeV. Interference with backgrounds with the same quantum numbers can easily shift peaks by 30 MeV. In Table 1, the $f_2(1640)$ state observed by GAMS in $\omega\omega$ is assigned as a $q\bar{q}$ radial excitation. It is anomalously narrow, possibly because the matrix element for $\pi\pi$ decays is fortuitously small because of a node in its radial wave function. Its $I = 1$ partner has been reported[23] as a peak at $\simeq 1690$ MeV in $\pi\pi\pi$.

The decays of $f_0(1505)$, $f_2(1770)$ and $f_0(2100)$ into $\sigma\sigma$ are striking. Both $TE1$ and $TM1$ gluons have one unit of orbital angular momentum tied up in their wave functions, which are described[24] by vector spherical harmonics with $L = 1$, $S = 1$, $J = 1$. If, when the glueball decays, this orbital angular momentum is transferred to the internal wave function of a $q\bar{q}$ state[25], it is natural that $q\bar{q}$ states $^3P_0$, $^3P_1$ and $^3P_2$ may figure strongly in glueball decays, i.e. σ, $f_1(1285)$ and $f_2(1270)$. This conjecture could solve another puzzle too. Glueball decays are naively expected to be flavour-blind. But if $q\bar{q}$ P-states are preferred in decays, the heavy K^* states will inhibit decays to final states involving kaons. This would explain the absence of $K\bar{K}$ decays, notably for $f_0(1505)$, which has now been observed by Crystal Barrel in $\pi\pi$, $\eta\eta$ and $\eta\eta'$, but not $K\bar{K}$. But then what is $\theta(1710)$, observed strongly in J/Ψ radiative decays? Obviously puzzles remain to be explored.

5 Three Gluon States

Suppose the masses of $f_0(1505)$ and $f_2(1770)$ arise from gluon mass plus zero point energy. Three gluon states, $(TE1)^3$ should then be expected around 1.5 $\times$ the mean mass of $f_0(1505)$ and $f_2(1770)$, i.e. 2450 MeV. Four states are to be expected with $J^{PC} = 0^{--}$, 1^{-+}, 2^{+-} and 3^{-+}. A rough estimate of 50 MeV for spin-splitting then

suggests masses 2375 MeV (0^{+-}) to 2525 MeV (3^{++}). The 1^{++} state should show up strongly in 3η decays through $f_0(1505)\eta$ with $L = 1$ and the 3^{++} state through $f_2(1770)\eta$, again with $L = 1$. An excellent place to look is in the $s-$channel for $\bar{p}p$ annihilation, since annihilation of three $q\bar{q}$ pairs generates three gluons. It is reasonable to expect a cross section which is a sizeable fraction of the unitarity limit, i.e. of order 1 mb for $\bar{p}p$ at $\simeq 2$ GeV/c. A search for these states by scanning the $\bar{p}$ momentum in steps of 150 MeV/c (equivalent to 50 MeV centre of mass energy) should be straightforward at the Fermilab $\bar{p}$ Ring. At LEAR, the available centre of mass energy is limited presently to 2410 MeV.

It is less easy to predict decay modes for exotic states 0^{+-} and 2^{+-}; $\rho\eta\pi$ with $L = 1$ is one suggestion.

6 Concluding Remarks

There are many outstanding experimental issues. It is crucial to confirm the existence of the 1910 MeV GAMS resonance and establish its quantum numbers definitively. If it has $J^{PC} = 1^{-+}$, a favoured decay mode is likely to be $f_1(1285)\eta$. It is also important to locate other decay modes of the seven states of Fig. 8. An understnading of $\theta(1710)$ remains a key issue: in general, decay modes involving kaons need thorough study. A spin-parity analysis of $J/\Psi \to \gamma(\eta\pi\pi)$ up to 2 GeV is urgently needed.

A search for $\bar{p}p \to 3g \to f_0(1505)\eta$ or $f_2(1770)\eta$ looks technically straightforward and timely.

In $q\bar{q}$ spectroscopy, the masses and decay modes of radial excitations around 1650-1700 MeV are important. It is particularly urgent to establish firmly the 0^+, 2^+ and 0^- states; the $I = 1$ components will provide guidance on which $I = 0$ states are more nearly $q\bar{q}$.

I am deeply indebted to my collaborators, particularly V.V. Anisovich, A.R. Cooper, A.V. Sarantsev and B.S. Zou for a great deal of hard work and stimulating discussions on these issues.

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