Resonances around 2 GeV: $q\bar{q}$ and glueballs

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Crystal Barrel data reveal systematics of $q\bar{q}$ resonances up to 2410 MeV. In particular, all expected $J^{PC} = 2^{++}$ $I = 0$ $q\bar{q}$ states may be identified in this range of masses M. For most J^{PC}, observed resonances lie close to straight line trajectories of M^2 v. radial quantum number, all having a uniform slope of 1.1 ± 0.03 GeV^2 per excitation. Tensor and spin-orbit splitting is small. Resonances with $L = J + 1$ lie $\sim$ 100 MeV higher in mass than those with $L = J - 1$.

Several states remain which do not fit naturally into this scheme, notably $f_0(1500)$, $f_0(2105)$, a broad 2^+ state at 1980 ± 50 MeV and a broad 0^- resonance at 2190 ± 40 MeV. Their mass ratios agree within small errors (3–14%) with Lattice QCD calculations of Morningstar and Peardon for glueballs. The $f_0(2105)$ appears strongly in the $\eta\eta$ channel, but not in $\pi\pi$. This indicates exotic character. If interpreted in terms of a mixed state $\cos\Phi(u\bar{u} + d\bar{d})/\sqrt{2} + \sin\Phi s\bar{s}$, then $\Phi = (65 \pm 6)^\circ$.

1. INTRODUCTION

The Crystal Barrel experiment has collected data at 9 momenta from 600 to 1940 MeV/c, corresponding to the mass range 1960–2410 MeV. One of the main aims has been to study s-channel resonances in a formation experiment $\bar{p}p \to R \to A + B$. Results have now been analysed for $I = 0$ final states $\pi^0\pi^0$, $\eta\eta$, $\eta\eta'$, $\eta\pi^0\pi^0$ [1] and $\omega\pi^0\pi^0$, and for $I = 1$ final states $\pi^0\eta$, $\pi^0\eta'$ [2], $3\pi^0$ [3] and $\eta\eta\pi^0$ [4,5]. At this conference, Anisovich [6] is presenting results on $\pi^0\eta$, $\pi^0\eta'$ and $3\pi^0$. Sarantsev [7] is presenting a coupled channel analysis of $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$, together with earlier data on $d\sigma/d\Omega$ and P for $\bar{p}p \to \pi^-\pi^+$.

I shall refer to Sarantsev's paper for details, but summarise the essential conclusions here. The analysis tests SU(3) relations between $\pi\pi$, $\eta\eta$ and $\eta\eta'$ channels. Decay amplitudes are parameterised as $\cos\Phi(u\bar{u} + d\bar{d})/\sqrt{2} + \sin\Phi s\bar{s}$. Almost all fitted resonances behave close to $(u\bar{u} + d\bar{d})/\sqrt{2}$ with only small mixing with $s\bar{s}$. However, one resonance, $f_0(2105)$, departs strongly from this pattern. It has been identified previously in $J/\psi \to \gamma(4\pi)$ [8] and in Crystal Barrel data on $\bar{p}p \to (\eta\eta)\pi^0$ [4]. A strong peak at this mass was first identified in E760 data [9] on $\bar{p}p \to \eta\eta\pi^0$, but no spin-parity analysis was made. It is now seen strongly in $\bar{p}p \to \eta\eta$, Fig. 1(a), but only weakly in $\bar{p}p \to \pi\pi$. The predicted ratio for $(u\bar{u} + d\bar{d})/\sqrt{2}$ is $\pi^0\pi^0/\eta\eta$ is $0.8^{-4} = 2.44$ from the quark content of the η, but the observed ratio is 0.71 ± 0.17. This requires $\Phi = (65 \pm 6)^\circ$. Such strong production in $\bar{p}p$ of a resonance with dominantly $s\bar{s}$ character is clearly anomalous, and suggests exotic character, either glueball or hybrid, (or a state strongly mixed with such

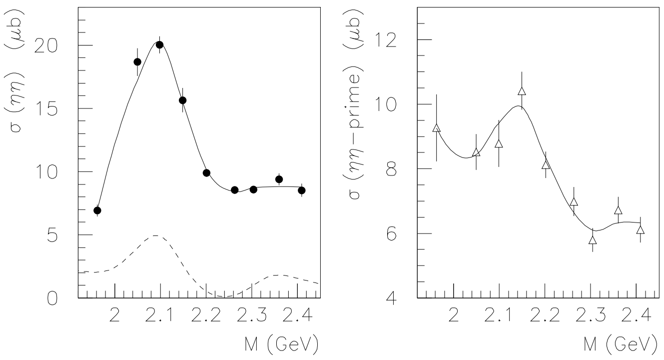

Figure 1. Cross sections integrated from $\cos\theta = 0$ to 0.85 for (a) $\bar{p}p \to \eta\eta$, (b) $\bar{p}p \to \eta\eta'$. Full curves show fits from the partial wave analysis [7]. The dashed curve in (a) shows the contribution of the 0^+ intensity.

components). Its strong production in J/ψ radiative decays points towards a glueball, which will be produced more strongly than a hybrid by a factor $1/\alpha_S^2$.

Table 1 shows the resonances which have appeared in the coupled channel analysis. If one includes other known resonances at lower masses, it is possible to construct a set of parallel straight-line trajectories of M^2 v. radial excitation number; here M is the mass. Fig. 2 shows several of these trajectories. For $J^P = 2^+$, four states may be assigned to a $q\bar{q}\ ^3P_2$ trajectory, namely $f_2(1270)$, $f_2(1565)$, $f_2(1910)$ and $f_2(2230)$, as in Fig 2(a). Two further 2^+ states, $f_2(2020)$ and $f_2(2300)$ lie on a higher-lying but parallel trajectory and are naturally assigned as $^3F_2$ states. The difference in mass may be interpreted as the result of a centrifugal barrier between q and $\bar{q}$, pushing the $^3F_2$ state up in mass. The $^3F_2$ states are almost degenerate with $^3F_4$ states, shown on Fig. 2(b) and $^3F_3$ shown on Fig. 2(c). This indicates small tensor and spin-orbit splitting.

The 0^+ states are tentatively attributed to a parallel trajectory on Fig. 2(d). The best established of these states is $f_0(1770)$, which has been identified in $J/\psi \to \gamma(4\pi)$ [8] and also in the $\eta\eta$ channel in Crystal Barrel data on $\bar{p}p \to (\eta\eta)\pi^0$ [5]. There were earlier tentative identifications in GAMS $\eta\eta$ data [10] (but without a firm J^P determination) and in $\pi\pi \to K\bar{K}$ [11]. A peak very close to this mass has also been observed in the E760 data [9]. Its mass and decay modes appear quite distinct from $f_J(1710)$. The straight-line trajectory through $f_0(1770)$ fits two further states at higher masses of 2005-2020 [12] and 2320 MeV and also $f_0(1370)$. It also goes naturally through $f_0(980)$ and will suit those who interpret this state as $q\bar{q}$ rather than a molecule. It also goes very close to the Adler zero! But it does not appear to accomodate $f_0(1500)$, which is an extra state.

2. EXOTIC STATES

It has been shown recently [13] that a broad 0^- resonance may be fitted to a large amount of data on J/ψ radiative decays to $\rho\rho$, $\omega\omega$, $K^*\bar{K}^*$, $\phi\phi$, $\eta\pi\pi$ and $K\bar{K}\pi$. Decays to the first four channels have coupling constants which are flavour-blind within errors of typically 30%. Together with the fact that it is observed strongly in a glue-rich process, this suggests a glueball. Its fitted mass is 2190 ± 50 MeV.

Table 1
Resonances fitted to data on $\bar{p}p \rightarrow \pi\pi$, $\eta\eta$ and $\eta\eta'$; errors cover the full range of systematic variation with varying ingredients; Φ is the flavour mixing angle.

J^P	Mass M (MeV)	Width Γ (MeV)	Φ (deg)
6^+	2485 ± 40	410 ± 90	(0)
5^-	2295 ± 30	235^{+65}_{-40}	
4^+	2300 ± 25	270 ± 50	22.9
4^+	2020 ± 12	170 ± 15	-26.1
3^-	2300^{+50}_{-80}	340 ± 150	
3^-	2210 ± 40	360 ± 55	
3^-	1960 ± 15	150 ± 25	
2^+	2300 ± 35	290 ± 50	-14.8
2^+	2230 ± 30	245 ± 45	7.5
2^+	2020 ± 30	275 ± 35	7.9
2^+	1910 ± 30	260 ± 40	1.1
1^-	2165 ± 40	160^{+140}_{-70}	
1^-	2005 ± 40	275 ± 75	
0^+	2320 ± 30	175 ± 45	15.1
0^+	2105 ± 15	200 ± 25	65 ± 6
0^+	2005 ± 30	305 ± 50	-0.5

The $f_0(1500)$ has long ago been suggested as a state with strong glueball admixture [14,15]. The original identification as a glueball was based simply on the fact that (a) it is too close in mass to $f_0(1370)$ to be a radial recurrence, (b) it is surprisingly narrow, (c) it couples surprisingly strongly to $\eta\eta$. However, it is certainly not a pure glueball, since it decays much more strongly to $\pi\pi$ than to $K\bar{K}$. Anisovich et al. [15] have fitted a large amount of data in $\pi\pi$, $\eta\eta$ and $K\bar{K}$ channels as superpositions of $\bar{q}q$ and gg states, and interpret $f_0(1500)$ as a mixed state with roughly 50% glueball content. The remaining 50% of the glueball appears in a very broad state of almost degenerate mass, 1530 MeV. It is argued [16] that a glueball will naturally mix with neighbouring $q\bar{q}$ states, absorbing their decay widths and becoming broad in the process.

There is now evidence from a number of sources for a broad 2^+ state of mass roughly 2 GeV and width $\sim$ 500 MeV. It was observed first in Central Production data [17] in the 4π channel. It also appears clearly in the $\eta\eta$ channel in Crystal Barrel data on $\bar{p}p \rightarrow (\eta\eta)\pi^0$ [4], shown here in Fig. 3. The figure shows decay angular distributions for successively increasing bins of $\eta\eta$ mass. At the lowest masses around 1500 MeV, the angular distribution is nearly flat and consistent with dominant $f_0(1500)$. As the mass increases, one observes a steadily growing asymmetry which requires a 2^+ component. It is much too broad to be explained as $f_2(1920)$ or $f_4(2050)$, and the angular momentum

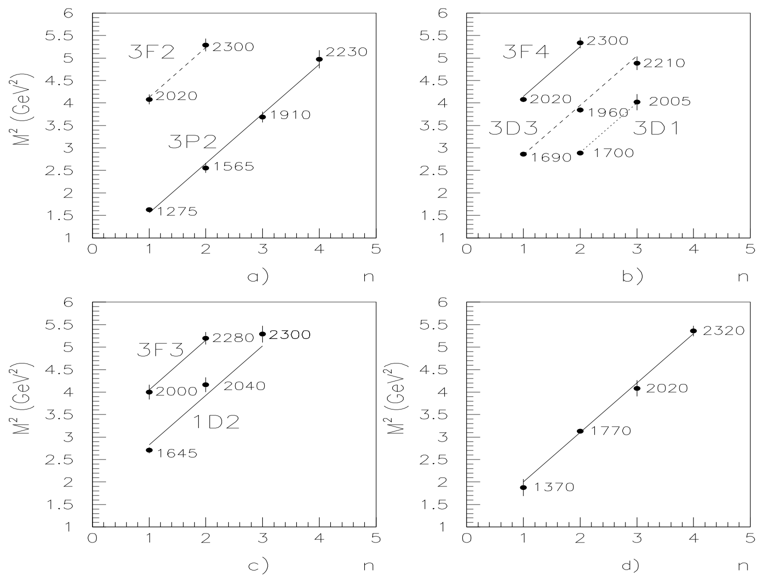

Figure 2. (a) Trajectories for $^3P_2$ states (full line) and $^3F_2$ (dashed) v. radial quantum number n; (b) likewise for 4^+ states (full line), 3^- (dashed) and 1^- (dotted); (c) for 3^+ and 2^- states; (d) trajectories for 0^+ states. Numerical values give masses in MeV.

analysis does not fit the latter. The fitted mass is 1980 ± 50 MeV with width 500 ± 100 MeV. More recently, it has been identified also in BES data on $J/\psi \to \gamma(4\pi)$ [18] and $\to K^*\bar{K}^*$ [19] with mass and width consistent with the earlier determinations.

3. LATTICE GAUGE CALCULATIONS

A recent improvement in Lattice Gauge calculations by Morningstar and Peardon [20] has led to accurate predictions for ratios of masses of glueballs. Predictions are shown in Table 2. They predict a second glueball with mass 1.54 ± 0.11 times that of the lowest one. There is still a large scale error on the calculations, of order 10–15%.

Table 2
Glueball mass ratios predicted by Morningstar and Peardon, compared with experimental candidates described in the text.

Ratio	Prediction	Experiment
$M(2^{++})/M(0^{++})$	1.39(4)	1.32(3)
$M(0^{-+})/M(0^{++})$	1.50(4)	1.46(3)
$M(0^{*++})/M(0^{++})$	1.54(11)	1.40(2)
$M(0^{-+})/M(2^{++})$	1.081(12)	1.043(36)

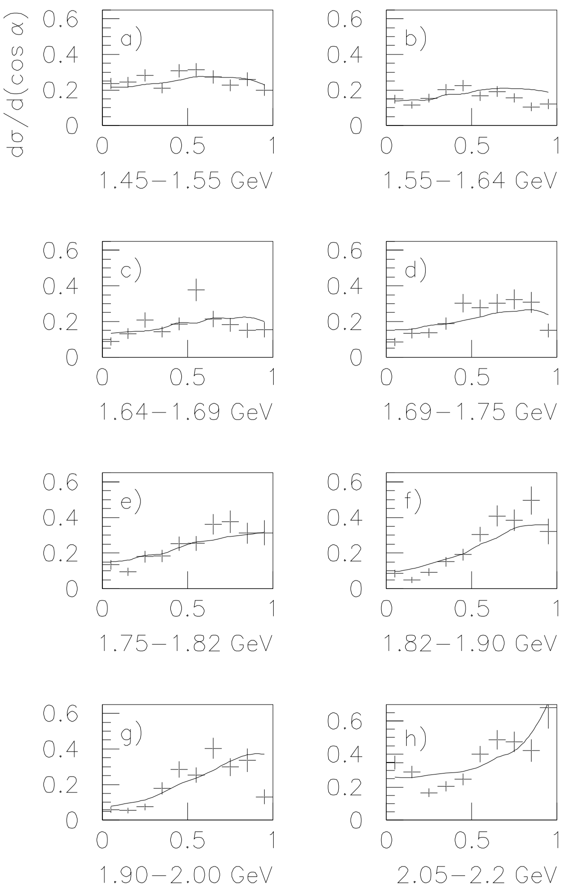

Figure 3. Decay angular distributions for several ranges of $M_{\eta\eta}$ in $\bar{p}p \to (\eta\eta)\pi^0$; (a)–(g) are at a beam momentum of 1525 MeV/c for mass intervals shown beneath each figure; (h) is at a beam momentum of 1940 MeV/c; curves are from the amplitude analysis.

Suppose we identify $f_0(1500)$, $f_0(2105)$, $f_2(1980)$ and $\eta(2190)$ as candidates for glueballs, for the reasons suggested above. Table 2 shows remarkably good agreement with the Lattice Gauge predictions. However, one must realise that calculations are still in the quenched approximation. Furthermore, it is clear that $f_0(1500)$ and $f_0(2105)$ are not pure glueballs, but must have some $q\bar{q}$ content. Further theoretical study of the expected mixing scheme is now important.

4. CAN WE UNDERSTAND LINDENBAUM'S $\phi\phi$ STATES?

Etkin et al. [21] observed three $\phi\phi$ states, the first in the S-wave peaking at ~ 2150 MeV, and the other two appearing in D-waves with spin $S = 0$ and 2 at 2300 and 2340 MeV. The production cross section is much higher than expected from conventional OZI-violating processes. My suggestion is that the presence of the broad 2^+ glueball in this mass range leads to mixing with $(u\bar{u} + d\bar{d})/\sqrt{2}$ and with $s\bar{s}$ states. States couple to $\pi\pi$

through the $(u\bar{u}+d\bar{d})$ component. Two $s\bar{s}$ states are to be expected in this mass range. The first is the $^3P_2$ partner of $f_2(1920)$, and appearance in S-wave decays to $\phi\phi$ is then natural. The second is the $^3F_2$ partner of $f_2(2020)$. I suggest that the first of these is responsible for the peak observed by Etkin et al. at 2150 MeV and the second for one or both of the peaks near 2300 MeV. The latter should appear naturally in the $\phi\phi$ D-wave. The question open at present is whether three fairly narrow $\phi\phi$ states are required, or whether one can get a fit of similar quality with 2 states + the broad $f_2(1980)$.

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