RAL-97-029
BHAM-HEP/97-03
16 June 1997

Implications of the Glueball-$q\overline{q}$ filter on the 1^{++} nonet

Frank E. Close[1]

Rutherford Appleton Laboratory
Chilton, Didcot, OX11 0QX, England

Andrew Kirk[2]

School of Physics and Astronomy
Birmingham University

Abstract

The application of our glueball-$q\bar{q}$ filter to the centrally produced $K\bar{K}\pi$ system shows that the $f_1(1285)$ and $f_1(1420)$ have the same behaviour; namely consistent with the $f_1(1420)$ being the partner to the $f_1(1285)$ in the $^3P_1$ nonet of axial mesons. We determine a flavour singlet-octet mixing angle of $\sim 50^o$ for this nonet and highlight that the existence of the supposed $f_1(1510)$ needs confirmation.

[1]e-mail: fec@v2.rl.ac.uk
[2]e-mail: ak@hep.ph.bham.ac.uk

1 Introduction

Recently we announced the discovery of a kinematic filter that separates $q\bar{q}$ and glueball states in central production[1] and illustrated its success in several channels[2]. This filter has now been applied to the process $pp \rightarrow p(K\bar{K}\pi)p$ where the prominent states in the $K\bar{K}\pi$ system have $J^{PC} = 1^{++}$[3]. In the present paper we shall argue that this new technique establishes the $f_1(1285)$ and $f_1(1420)$ as $q\bar{q}$ states, in contrast to a widespread opinion that the nonet contains an $f_1(1510)$ while the $f_1(1420)$ is a non-$q\bar{q}$ state[4] or $K^*\overline{K}$ molecule [5, 6].

We shall show that there is a substantial body of data consistent with the $D \equiv f_1$ (1285) and $E \equiv f_1$ (1420) belonging to a $q\bar{q}$ nonet with a consistent mixing

$$D \simeq \mid n\bar{n}\rangle - \delta \mid s\bar{s}\rangle$$
$$E \simeq \mid s\bar{s}\rangle + \delta \mid n\bar{n}\rangle$$

with $\delta \simeq$ 0.4 - 0.5 ($n\bar{n} \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$). The essential feature is the $n\bar{n}(s\bar{s})$ dominance in $D(E)$ with destructive (constructive) admixture of the other flavour.

We shall also question the existence or interpretation of the supposed $f_1(1510)$, highlight possible anomalies in the data and identify critical questions for experimental investigation.

1.1 A brief history

Originally the E/$f_1(1420)$ was thought to be the $s\overline{s}$ isoscalar member of the ground state 1^{++} nonet, the other members being the $a_1(1260)$ triplet, the $K_1(1270/1400)$ and the $f_1(1285)$. The E/$f_1(1420)$ was found to decay dominantly to $K^*\overline{K}$ hence reinforcing its $s\overline{s}$ assignment. However, problems with this interpretation then began to emerge. Firstly, it is commonly accepted that $s\overline{s}$ objects should be preferentially produced in K^- incident experiments but in the study of the reaction

$$K^-p \rightarrow K^0_S K^\pm \pi^\mp \Lambda$$

two experiments [7, 8] observed only weak evidence for a E/$f_1(1420)$ signal. Instead they found evidence for a new J^{PC} = 1^{++} state with a mass of

1.53 GeV and a width of 100 MeV, called the D$'/f_1(1510)$. It was suggested that this state is a better candidate for the $s\overline{s}$ member of the 1^{++} nonet based on the fact that its production was more compatible with that of an $s\overline{s}$ state. Further evidence for this classification came from studying the nonet mixing angle from various sources [7, 9] and from a study of hadronic J/ψ decay [10, 11].

Therefore, the 1^{++} nonet appears to have ten members with the E$/f_1(1420)$ thought to be the extra state. As a 1^{++} state its mass is generally regarded as too low to be a glueball (lattice QCD predicts the lightest 1^{++} glueball to be at 4.0 ± 0.5 GeV [12]) and suggestions have been made that it is a four quark state [4] or $K^*\overline{K}$ molecule [5, 6] (there is however no sign of an $I = 1$ partner).

In this paper we will reanalyse the data on the isoscalar 1^{++} states. The new input in this paper are the data from central production which show that the $f_1(1285)$ and the $f_1(1420)$ both behave the same with dp_T, specifically in the way that parallels other standard $q\overline{q}$ states [2].

1.2 Criticism of Evidence for the $f_1(1510)$

The PDG [13] cites 4 references for the $f_1(1510)$: the two original K^-p experiments [7, 8], a π^-p experiment [14] and a $\gamma\gamma^*$ experiment [15]. The masses and widths observed in each experiment are given in table 1. However, we would highlight some questions about these assignments.

The PDG chooses the values coming from the π^-p experiment performed at the MPS [14] as the parameters it quotes for the $f_1(1510)$. This choice is rather bizarre since the peak observed is only at best a 2.5σ effect (see fig. 1) and it does not appear in the 1^{++} wave (see fig. 2b where no significant structure is observed in the 1^{++} wave in the 1.5 GeV region). The only hint for a 1^{++} assignment comes from a statistically weak phase motion. We regard it as significant that the same group, in a high statistics experiment using a K^- beam subsequently found no evidence for this state [16].

The original evidence for the $f_1(1510)$ (or as it was originally called, the D$'/f_1(1530)$) had come from the (low statistics) study of the $K^0_SK^\pm\pi^\mp$ system in K^-p interactions. Two experiments reported evidence for an axial meson in the 1.53 mass region though different analysis methods were needed to extract the signal. The evidence for the state comes from an observation of an asymmetry in the Dalitz plot of the $K^0_SK^\pm\pi^\mp$ system. In the one experiment [7] this asymmetry is interpreted as due to incoherent K^* production; in the second experiment [8] it is explained as being due to an interference between the hypothesised $f_1(1510)$ and the $h_1(1380)$.

The mutual consistency of the two experimental signals is debatable. It is notable that both experiments suffer from low statistics; by contrast two subsequent high statistics studies of the $K^- p$ reaction [16, 17] show no evidence for a 1^{++} signal in the 1.5 GeV region.

More recent experiments raise further questions concerning the $f_1(1510)$. No $f_1(1510)$ signal occurs in central production where the other 1^{++} states are clearly seen, nor is it observed in $p\overline{p}$ annihilations. The only other suggestion of a narrow 1^{++} state in the 1.5 GeV mass region comes from BES [18]. At BES a preliminary partial wave analysis of the reaction $J/\psi \to \gamma(K^0_S K^\pm \pi^\mp)$ claims a 1^{++} state in the region of 1.5 GeV. However, we note that this is in disagrees with results from from MARKIII [19] and DM2 [20] which had no evidence for a 1^{++} signal in the 1.5 GeV region of radiative J/ψ decay.

The signal observed in $\gamma\gamma^*$ interactions is in the $\pi^+\pi^-\pi^0\pi^0$ channel which is bizarre if it is supposed to be an $s\bar{s}$ state. Furthermore there is no direct evidence that the state has $J^P = 1^+$ other than an unusual q^2 dependence. We regard as significant the fact that the same group (TPC/2γ) do not see any evidence for a state at 1.5 GeV in the $K^0_S K^\pm \pi^\mp$ final state [21].

There are also theoretical arguments that make it unlikely that any 1^{++} state at $\sim$ 1510 MeV could be a $^3P_1$ $q\bar{q}$ state as at such a mass the width into $K^*\overline{K}$ would be very broad [22]. Explicit calculations of the axial meson widths are given in ref. [22] and are more general than the detailed model. The empirical feature to note is that the width $a_1 \to \rho\pi$ sets the scale and agrees with the model. The physics is that the S-wave decays rapidly turn on with increasing phase space, making the widths large and the mesons hard to establish if $M \geq 1450$ MeV. The width of the candidate $f_1(1285)$ and $f_1(1420)$ are compatible with the model, whereas $f_1(1510)$ with "narrow" width of $\sim 35 \pm 15$MeV[13] would be hard to understand. Thus our point of departure is to suppose that the $f_1(1420)$ and $f_1(1285)$ are driven by the $q\bar{q}$ nonet and that the $f_1(1510)$ is either an artifact or a novel dynamic state.

1.3 Information from central production

In central production the $f_1(1285)$ and E/$f_1(1420)$ are clearly observed [23]. Furthermore they exhibit the same behaviour as a function of the dp_T filter[1, 3], appearing sharply when $dp_T > 0.5$ GeV, as do other established ^3P_J $q\bar{q}$ states, and vanishing as $dp_T \to 0$. This is consistent with the $f_1(1420)$ having the same dynamical structure as the $f_1(1285)$, namely $^3P_1(q\bar{q})$. By contrast, there is no signal for the $f_1(1510)$ at any dp_T.

Nor is there any evidence for any 0^{-+} contribution in the 1.4 GeV region. In fact it is interesting to note that 0^{-+} states are suppressed in central production relative to 1^{++} states [24]. Both the η and η' signals are suppressed at small four-momentum transfers where Double Pomeron Exchange (DPE) is believed to be dominant [24, 25]. Hence it could be conjectured that 0^{-+} objects do not couple to DPE. This hypothesis could further be tested by measuring the cross section of the production of η' as a function of energy. The η' cross section has been measured [26] in pp interactions at an incident beam momentum of 85 and 300 GeV/c and gives

$$\frac{\sigma_{85}(\eta')}{\sigma_{300}(\eta')} = 0.2 \pm 0.05 \tag{1}$$

which is consistent with the η' being produced by Reggeon exchange [27].

This suppression of 0^{-+} states in central production has a very important application since it can help us in untangling other experiments that see both 0^{-+} and 1^{++} states. For example, in the centrally produced $K^0_S K^\pm \pi^\mp$ mass spectrum (see fig. 3a) clear signals are observed of the $f_1(1285)$ and $f_1(1420)$. However, as can be seen from fig. 3b, in the centrally produced $\eta\pi^+\pi^-$ spectrum there are clear signals of the η' and $f_1(1285)$ but no signal in the 1.4 GeV region. Therefore, we can infer that any states observed elsewhere prominently in the 1.4 GeV region of the $\eta\pi\pi$ mass spectrum are **not** 1^{++} and are likely to be pseudoscalar. This fact will be exploited later when we come to discuss hadronic J/ψ decays.

2 The 1^{++} nonet

2.1 Introduction

In this section we show that the $D \equiv f_1$ (1285) and $E \equiv f_1$ (1420) form a $q\bar{q}$ nonet with a consistent mixing

$$D \simeq \mid n\bar{n}\rangle - \delta \mid s\bar{s}\rangle$$

$$E \simeq \mid s\bar{s}\rangle + \delta \mid n\bar{n}\rangle$$

with $\delta \simeq 0.4$ - 0.5 ($n\bar{n} \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$). The essential feature is the $n\bar{n}(s\bar{s})$ dominance in $D(E)$ with destructive (constructive) admixture of the other flavour. Expressed in **1-8** flavour basis we have

$$D = \cos\theta \mid 1\rangle + \sin\theta \mid 8\rangle$$
$$E = \cos\theta \mid 8\rangle - \sin\theta \mid 1\rangle$$

where $\mid 8\rangle \equiv \frac{1}{\sqrt{3}} \mid n\bar{n} - \sqrt{2}s\bar{s}\rangle$ and we shall find that $\theta \sim 50^o$.

2.2 Mass formula

¿From the Gell Mann Okubo Mass formula

$$cos^2(\theta) = \frac{2m_{K_1} + 2m_{K_2} - m_{a_1} - 3m_E}{3(m_D - m_E)} \tag{2}$$

we get $\theta = (52.5^{+6.7}_{-5.0})^0$. It should be noted that this mass formula assumes that symmetry breaking in the masses is pure octet; if the $s\overline{s}$ were initialy at 1480 MeV, as is predicted in the Godfrey-Isgur model [28], then the physical resonance could be shifted to the $f_1(1420)$ mass due to the presence of the $K^*\overline{K}$ threshold through a mechanism similar to that suggested in ref. [29]. Such a mass shift would imply $\theta = 43^0$ which highlights the lack of sensitivity of the mass formula and the artificial reliance on pure $q\overline{q}$ interpretation.

2.3 SU(3) coupling formula

¿From the SU(3) coupling formula [30] an expression can be derived for the nonet mixing angle in terms of the partial decay rates and reduced couplings such that

$$cos^2(\theta) = \frac{\Gamma(E \to K^*\overline{K})m_E^2}{< q_{K^*} > g_A^2} \tag{3}$$

where g_A^2 is derived from the decay $a_1(1270) \to \rho\pi$ and gives $\theta = (63^{+5}_{-4})^0$. This calculation assumes SU(3) symmetry for decays involving $s\overline{s}$ and $n\overline{n}$ creation. If this constraint is relaxed, θ can be shifted considerably in either direction.

2.4 Radiative decay of $f_1(1285)$

¿From radiative $f_1(1285)$ decays to a ϕ and ρ the nonet mixing angle can be calculated from

$$\frac{Br(f_1(1285) \to \phi\gamma)}{Br(f_1(1285) \to \rho\gamma)} = \frac{4}{9}\frac{q^3(f_1 \to \phi\gamma)}{q^3(f_1 \to \rho\gamma)} tan^2(\theta - \theta_{ideal}) \tag{4}$$

where $\theta_{ideal} = 35.3^0$ is the ideal nonet mixing angle. The PDG [13] gives Br($f_1(1285) \to \phi\gamma) = (8.0 \pm 3.1)10^{-4}$ and Br($f_1(1285) \to \rho\gamma) = (6.6 \pm 3.1)10^{-2}$ which implies $\theta = (56^{+4}_{-5})^0$.

2.5 $\gamma\gamma^*$ and radiative J/ψ decays

Here we reassess earlier analyses of $\gamma\gamma^*$ and J/ψ radiative decays, incorporating our new results from central production. Recall that we defined

$$D = \cos\theta \mid 1\rangle + \sin\theta \mid 8\rangle$$
$$E = \cos\theta \mid 8\rangle - \sin\theta \mid 1\rangle$$

where $\mid 8\rangle \equiv \frac{1}{\sqrt{3}} \mid n\bar{n} - \sqrt{2}s\bar{s}\rangle$. For simplicity we shall ignore phase space and form factors; these tend to cancel out in ratios, do not essentially affect our conclusions and enable readers to modify according to taste.

The initial input is from radiative J/ψ decays where the branching ratio of the J/ψ to γD and γE are related by

$$\frac{B(J/\psi \to \gamma E)}{B(J/\psi \to \gamma D)} = \frac{0.83 \pm 0.15}{0.65 \pm 0.10}\frac{1}{B(E \to K\bar{K}\pi)} \equiv tan^2\theta \tag{5}$$

and if we assume that $B(E \to K\bar{K}\pi) = 1$ this gives $\theta = 48.5^{+3}_{-3.8}$. The second input is from $\gamma\gamma^*$ interactions where

$$\frac{\Gamma(E \to \gamma\gamma^*)}{\Gamma(D \to \gamma\gamma^*)} = \frac{0.34 \pm 0.18}{B(E \to K\bar{K}\pi)} \equiv tan^2(\theta - 19.5^0) \tag{6}$$

and again, assuming $B(E \to K\bar{K}\pi) = 1$ gives $\theta = 49.7^{+5.6}_{-8.0}$. The data used here are from the PDG [13] and the θ dependence is derived in ref.[36].

Independent of $B(E \to K\bar{K}\pi)$ we can calculate the ratio of eqs (5) and (6) which constrains

$$f(\theta) = \frac{tan^2(\theta - 19.5^0)}{\tan^2\theta} = 0.27 \pm 0.15$$

In fig. 4 $f(\theta)$ is displayed along with the mean value and the one sigma bands. As can be seen, within one sigma there are three regions of solution (a) $12^0 - 14.5^0$ (b) 96.5 ± 1.5^0 (c) $31.5^0 - 78^0$. However we can eliminate (a) and (b), and tighten (c) as follows

(a) The fact that $B(E \to K\bar{K}\pi) \leq 1$ implies, via eqn(5), that $B(J/\psi \to \gamma D) \lesssim B(J/\psi \to \gamma E)$. Small values of θ, as in solution (a), imply $\mid D\rangle \simeq \mid 1\rangle$, $\mid E\rangle \simeq \mid 8\rangle$ and hence $B(J/\psi \to \gamma D) \gg B(J/\psi \to \gamma E)$, inconsistent with the above. This is a general result, insensitive to phase space or form factors.

(b) $\theta \simeq 90^0$ implies that $B(J/\psi \to \gamma E) \gg B(J/\psi \to \gamma D)$. This would only be attainable if $B(E \to K\bar{K}\pi) \to 0$. However this is unlikely for the following reasons

(i) The data from central production (section 1.3 and fig.3) show a prominent signal in $E \to K\bar{K}\pi$ and no presence in $E \to \eta\pi\pi$ which suggests $B(E \to K\bar{K}\pi)$ is not small.

(ii) The quark model calculations of ref.[22] expect that for 1^{++} at this mass both $\mid s\bar{s}\rangle$ and $\mid n\bar{n}\rangle$ dominantly couple to KK^*. The phases with $\theta \simeq 90^0$ give constructive contribution for $E \to K\bar{K}\pi$ which argues for $B(E \to K\bar{K}\pi) \to 1$. These general conclusions are insensitive to phase space and form factors.

(c) The solutions cover the range

$$\begin{aligned} D &= 0.84 \mid 1\rangle + 0.54 \mid 8\rangle \qquad \theta = 31.5^0 \\ D &= 0.34 \mid 1\rangle + 0.94 \mid 8\rangle \qquad \theta = 78^0 \end{aligned}$$

However, the lower end of this range is eliminated by

$$\frac{B(J/\psi \to \gamma E)}{B(J/\psi \to \gamma D)} \gtrsim \frac{0.9}{B(E \to K\bar{K}\pi)}$$

at 1σ, which restricts the mixing angle $\theta \gtrsim 40^0$ (the solution in ref. [36] corresponds to $\theta = 55^0$).

Although the mixing in the singlet-octet basis appears to be constrained somewhat imprecisely, the qualitative and robust feature of the solutions is more transparent in the flavour basis

$$\begin{aligned} D &= 0.98 \mid n\bar{n}\rangle - 0.14 \mid s\bar{s}\rangle \qquad \theta = 40^0 \\ D &= 0.82 \mid n\bar{n}\rangle - 0.56 \mid s\bar{s}\rangle \qquad \theta = 78^0 \end{aligned}$$

which shows the dominance of $\mid n\bar{n}\rangle$ and negative phase relative to $\mid s\bar{s}\rangle$. Qualitatively it is this destructive phase that reduces $J/\psi \to \gamma D$ relative to $J/\psi \to \gamma E$ due to $\langle gg \mid n\bar{n}\rangle$ fighting $\langle gg \mid s\bar{s}\rangle$ in $J/\psi \to \gamma gg \to \gamma(D, E)$. The absolute values will be affected slightly by phase space and form factors but these generic features are robust. The $\theta \to 40^0$ correlates with $B(E \to K\bar{K}\pi) \to 1$, whereas the $\theta \to 78^0$ has $B(E \to K\bar{K}\pi) < 0.1$. The $n\bar{n}$ dominance will cause

$$B(J/\psi \to D\omega(n\bar{n})) > B(J/\psi \to D\phi(s\bar{s}))$$

(we discuss this later).

The $\gamma\gamma$ widths also impose a constraint where from eqn (6) the larger θ correlate with small $B(E \to K\bar{K}\pi)$. The data from central production suggest that this branching ratio is large; the quark model analysis[22] of quasi-two body decays suggests that this will indeed be near 100%.

2.6 Solving the hadronic J/ψ problem

It is interesting that these various data are independently consistent with $\theta \sim 50^o$ whereby

$$D \simeq \mid n\bar{n}\rangle - \delta \mid s\bar{s}\rangle$$
$$E \simeq \mid s\bar{s}\rangle + \delta \mid n\bar{n}\rangle$$

with $\delta \simeq 0.4$ - 0.5. We now examine what has been a cause for the uncertainty in the assignment of the $f_1(1420)$ as the $s\overline{s}$ member of the 1^{++} nonet, namely the claim that it is seen opposite the ω and not the ϕ in hadronic J/ψ decays. In this section we shall discuss the basis on which this claim is made.

In hadronic J/ψ decays a signal is observed opposite the ω in the 1.4 GeV region of both the $K^0_S K^\pm \pi^\mp$ and $\eta\pi\pi$ mass spectrum. A spin analysis favours $J^{PC} = 1^{++}$ for both states. In the $K^0_S K^\pm \pi^\mp$ channel the structure has a mass of 1438 $\pm$ 4 MeV which is 3 σ higher than the mass of the $f_1(1420)$, and a width of 94 $\pm$ 12 MeV. The state is also found to decay to $K^*\overline{K}$ and $a_0(980)\pi$ in the ratio 2:1 which is in contradiction to the dominance of the $K^*\overline{K}$ decay mode found for the $f_1(1420)$ in radiative J/ψ decays and in central production.

Firstly it should be remembered that the hadronic analysis on which this claim is based was performed prior to the discovery that the ι peak observed in radiative J/ψ decays has a detailed infrastructure. Secondly from the lack of a $f_1(1420)$ signal in the $\eta\pi\pi$ mass spectrum of central production (fig. 3) we would claim that the state observed in the $\eta\pi\pi$ mass spectrum opposite the ω is not the $f_1(1420)$ and we conjecture that any signal seen in the 1.4 GeV region of the $\eta\pi\pi$ mass spectrum must be pseudoscalar. This then casts doubt on the 1^{++} assignment of the peak in the 1.4 GeV region of the $K^0_S K^{\pm}\pi^{\mp}$ mass spectrum.

We now consider further checks that can be made of this nonet structure. As $\theta \to 78^0$ and ignoring phase space we would expect as a minimum that

$$\frac{B(J/\psi \to \omega D)}{B(J/\psi \to \phi D)} \gtrsim 2$$

assuming that $\omega \equiv n\bar{n}, \phi \equiv s\bar{s}$. If $\theta < 78^0$, or including phase space, this ratio rises; conversely if ω or ϕ are not ideal flavour states, the ratio will fall. The current best estimate for this value is 2.7 $\pm$ 1.8 from ref. [37]. This ratio should be measured more precisely at Beijing or a future τ-charm factory with special care to ensure separation of a possible $\eta(1295)$ signal from the $f_1(1285)$ (D) in the $\eta\pi\pi$ channel. An analysis of the $K\bar{K}\pi$ channel involves more detailed combinatorics in the $\phi K\bar{K}\pi$ but may enable $\omega D/\omega E$ to be extracted. Phase space and form factor effects tend to cancel in the $\phi D/\omega E$ ratio. These questions have taken on renewed interest in view of recent work on the presence of higher (multiquark) components in light mesons [38].

2.7 Criticism of claims for the non-$q\overline{q}$ nature of the $f_1(1420)$

The most striking claim for the non-$q\overline{q}$ nature of the $f_1(1420)$ has been that in spite of its dominant decay to $K^*\overline{K}$ it is not produced strongly in K^-p interactions where $s\overline{s}$ states are usually seen. However, this claim is refuted by the LEPTON-F experiment which has studied $\pi^-p \to K^+K^-\pi^0 n$ and $K^-p \to K^+K^-\pi^0 Y$ [17]. In the π^-p reaction they have a strong $f_1(1285)$ signal but there is no statistically significant structure in the 1.4 GeV region, from which they infer that

$$tan^2(\theta - \theta_{ideal}) = \frac{\sigma(\pi^-p \to f_1(1420)n)}{\sigma(\pi^-p \to f_1(1285)n)} < 0.05 \qquad (7)$$

and hence $\theta < 48^o$. This is consistent with a dominant $s\bar{s}$ content in the $f_1(1420)$ and with our foregoing analyses. Furthermore, in the reaction $K^- p \to K^+ K^- \pi^o Y$ they observe a clear signal in the $f_1(1420)$ region from which they calculate that

$$\frac{K^- p \to f_1(1420)Y}{\pi^- p \to f_1(1420)n} > 10. \tag{8}$$

again consistent with a dominant $s\bar{s}$ content.

In addition, one of the early $K^- p$ experiments [7] which claimed a signal for the $D'/f_1(1530)$ also claimed a peak in the 1.42 GeV region consistent with being the $f_1(1420)$. Therefore, in summary, it is not so simple to claim that the $f_1(1420)$ is not seen in K^- incident experiments.

Fig. 5 shows a summary of the derivation of the singlet-octet mixing angle from the different methods discussed above, assuming that the $f_1(1285)$ and the $f_1(1420)$ are the isoscalar members of the nonet. As can be seen the angle calculated from the different methods are consistent and give an average value of 53^0 (excluding the LEPTON-F upper limit). It should be noted that the errors shown in fig. 5 represent the experimental error on the measured quantities only. Errors due to the theoretical uncertainty in the derivation of the formulae used can only help to make the values more consistent.

3 Outstanding problems and Summary

The major problem is to determine the number of 1^{++} states. In summary there is no doubt that the $f_1(1285)$ and $f_1(1420)$ exist. Without the existence of the $f_1(1510)$ the only major problem with describing the $f_1(1420)$ as the (dominantly) $s\bar{s}$ nonet member has been the possibility that it is not produced copiously in $K^- p$ reactions, however, this claim would be denied by at least one experiment [17]. A summary of the $f_1(1510)$ is that two $K^- p$ experiments have weak evidence for it, and two others do not see it. One J/ψ experiment may see it while two do not and there is a small possibility that it is observed in $\pi^- p$ reactions.

The other major uncertainty is in the J/ψ hadronic decays. A reanalysis of the ι region is needed allowing for modern insights into its detailed infrastructure and our conjecture on the role of 0^{-+} and 1^{++} in this region.

In J/ψ radiative decay each experiment has a different interpretation [18, 19, 20]. The analysis of ref.[36] also may have relevant constraints in this regard. These questions should be reexamined at BES and at a future τ-charm factory.

Data on $K^- p \to K_s^0 K_s^0 \pi^0 Y$ can access $C = +$ and hence eliminate uncertainties involving possible $C = -$ content that have clouded some analyses [8, 16]. However since such data are unlikely in the immediate future, what should be performed is a reanalysis of the MPS data since there is an inconsistency in them; in π^- incident a signal for the $f_1(1510)$ is claimed while in K^- incident there is no signal.

The conclusion reached from the analysis presented in this paper is that without confirmation of the existence of the $f_1(1510)$ the isoscalar members of the $J^{PC} = 1^{++}$ nonet should be considered to be the $f_1(1285)$ and $f_1(1420)$ with a singlet-octet mixing angle of approximately 50^0. Furthermore, any prominent states in the 1.4 GeV region of $\eta\pi\pi$ are unlikely to be 1^{++} and are likely to be 0^{-+}.

References

[1] F.E. Close and A. Kirk, Phys. Lett. **B397** (1997) 333.

[2] D. Barberis *et al.,* Phys. Lett. **B397** (1997) 339.

[3] D. Barberis *et al.,* Submitted to Physics Letters.

[4] F.E. Close, Rep. Prog. Phys. **51** (1988) 833;
D. Caldwell, Mod. Phys. Lett. **A2** (1987) 771.

[5] J. Weinstein, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 400.

[6] R.S. Longacre Phys. Rev **D42** (1990) 874.

[7] Ph. Gavillet *et al.,* Zeit. Phys. **C16** (1982) 119.

[8] D.Aston *et al.*, Phys. Lett. **B201** (1988) 573.

[9] O.Oneda, M.D. Slaughter and T. Teshina, Proceedings of Hadron 89, (1989), 423.

[10] S. Meshkov, W. Palmer and S. Pinsky DOE-ER 01545-38.

[11] G. Eigen CALT-68-1791 (1992).

[12] G.Bali et al (UKQCD Collaboration) Physics Letters **B309** (1993) 378.

[13] Particle Data Group Phys Rev. **D54** (1996) 1.

[14] A. Birman *et al.,* Phys. Rev. Lett. **61** (1988) 1557.

[15] D. Bauer *et al.,* Phys. Rev. **D48** (1993) 3976.

[16] E. King *et al.,* Nucl. Phys **B21** (proc. suppl.) (1991) 11.

[17] S.I. Bityukov *et al.,* Sov. J. Nucl. Phys. **39** (1984) 735.

[18] Y. Huang, Proc. of Hadron 95, (1995) 518.

[19] Z. Bai *et al.,* Phys. Rev. Lett. **65** (1990) 2507.

[20] J.E. Augustin *et al.,* Phys. Rev. **D46** (1992) 1951.

[21] H. Aihara *et al.,* Phys. Rev. **D38** (1988) 1.

[22] T. Barnes *et al.,* Phys. Rev. **D55** (1997) 4157.

[23] T. Armstrong *et al.,* Phys. Lett. **B146** (1984) 273;
T. Armstrong *et al.,* Zeit. Phys. **C34** (1987) 23;
T. Armstrong *et al.,* Phys. Lett. **B221** (1989) 216;
T. Armstrong *et al.,* Zeit. Phys. **C56** (1992) 29.

[24] T. Armstrong *et al.,* Zeit. Phys. **C52** (1991) 389.

[25] T. Armstrong *et al.*, Zeit. Phys. **C48** (1990) 213.

[26] WA76 Collaboration unpublished.

[27] S.N. Ganguli and D.P. Roy, Phys. Rep. **67** (1980) 203.

[28] S. Godfrey and N. Isgur, Phys. Rev. **D32** (1985) 189.

[29] N.A. Tornqvist, Zeit. Phys. **C68** (1995) 647.

[30] R.K. Carnegie *et al.*, Phys. Lett. **B68** (1977) 287;
M. Mazzucato *et al.*, Nucl. Phys. **B156** (1979) 532.

[31] H. Aihara *et al.,* Phys. Rev. **D38** (1988) 1;
G. Gidal *et al.*, Phys. Rev. Lett. **59** (1987) 2016;
P. Hill *et al.*, Zeit. Phys. **C42** (1989) 355;
H.J. Behrend *et al.,* Zeit. Phys. **C42** (1989) 355;
M. Feindt, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 501.

[32] S. Yellin, Nucl. Phys. **B21** (1991) 75.

[33] C.N. Yang, Phys. Rev. **77** (1950) 242.

[34] D.O. Caldwell, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 465.

[35] F.M. Renard, Nuovo Cimento **80** (1984) 1;
R.N. Cahn, Phys. Rev. **D35** (1987) 3342;
Z.P. Li, F.E. Close and T. Barnes, Phys. Rev. **D43** (1991) 2161;
F.E. Close and Z.P. Li Zeit. Phys. **C54** (1992) 147.

[36] F.E. Close, G. Farrar and Z.P. Li, Phys. Rev. **D55** (1997) 5749.

[37] L. Köpke and N. Wermes, Phys. Rep. **174** (1989) 67.

[38] S.J. Brodsky and M. Karliner, hep-ph/9704379.

Tables

Table 1: Parameters of resonances in the fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum.

Reaction	Ref	Mass (MeV)	Width (MeV)	Observed decay mode	J^{PC} determined
K^-p	[7]	1526 ± 6	107 ± 15	$K^*\overline{K}$	Yes
K^-p	[8]	1530 ± 10	100 ± 40	$K^*\overline{K}$	Yes
π^-p	[14]	1512 ± 4	35 ± 15	$K^*\overline{K}$	No
$\gamma\gamma^*$	[15]	1525 ± 25	200 ± 50	$\pi^+\pi^-\pi^0\pi^0$	No

Figures

Figure 1: The $K_S^0 K^\pm \pi^\mp$ mass spectrum from ref. [14]. The full circles are for $0.0 \leq$ -t < 1.0 GeV^2/c^2 and the open circles are for $0.45 \leq$ -t < 1.0 GeV^2/c^2.

Figure 2: The results of the partial wave analysis from ref. [14]. a) The 0^{-+} wave, b) the 1^{++} wave, c) the 1^{+-} wave and d) the background (phase space) contribution.

Figure 3: a) The $K_S^0 K^\pm \pi^\mp$ and b) the $\eta\pi^+\pi^-$ mass spectrum from central production [24].

Figure 4: The function $\frac{tan^2(\theta - 19.5^0)}{tan^2\theta}$ with the 0.27 $\pm$0.15 region shown.

Figure 5: Summary of the 1^{++} singlet-octet mixing angle.

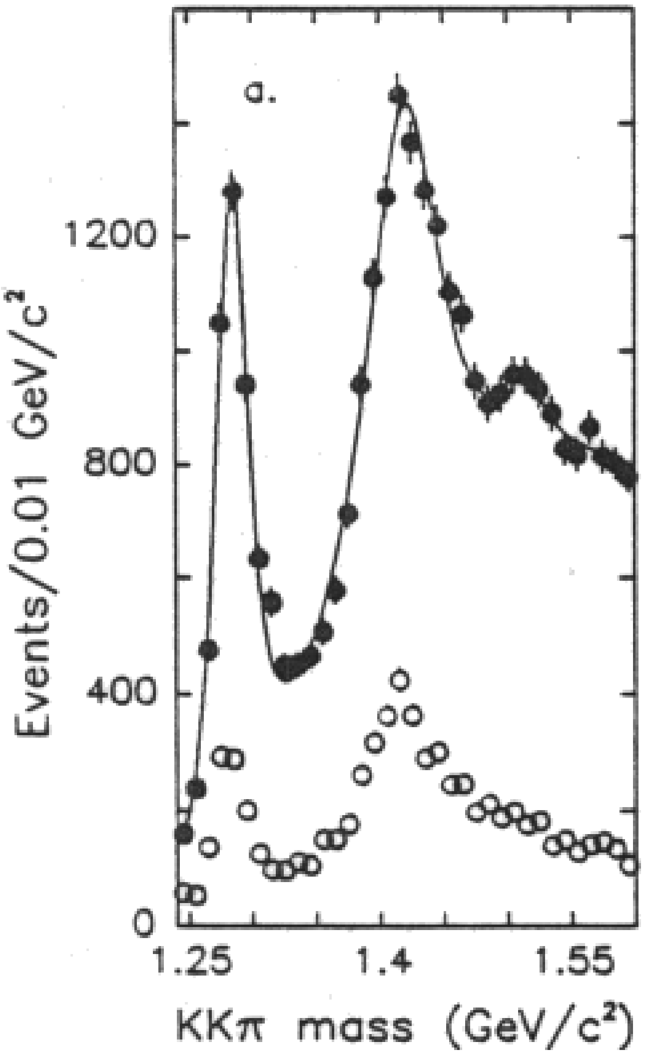
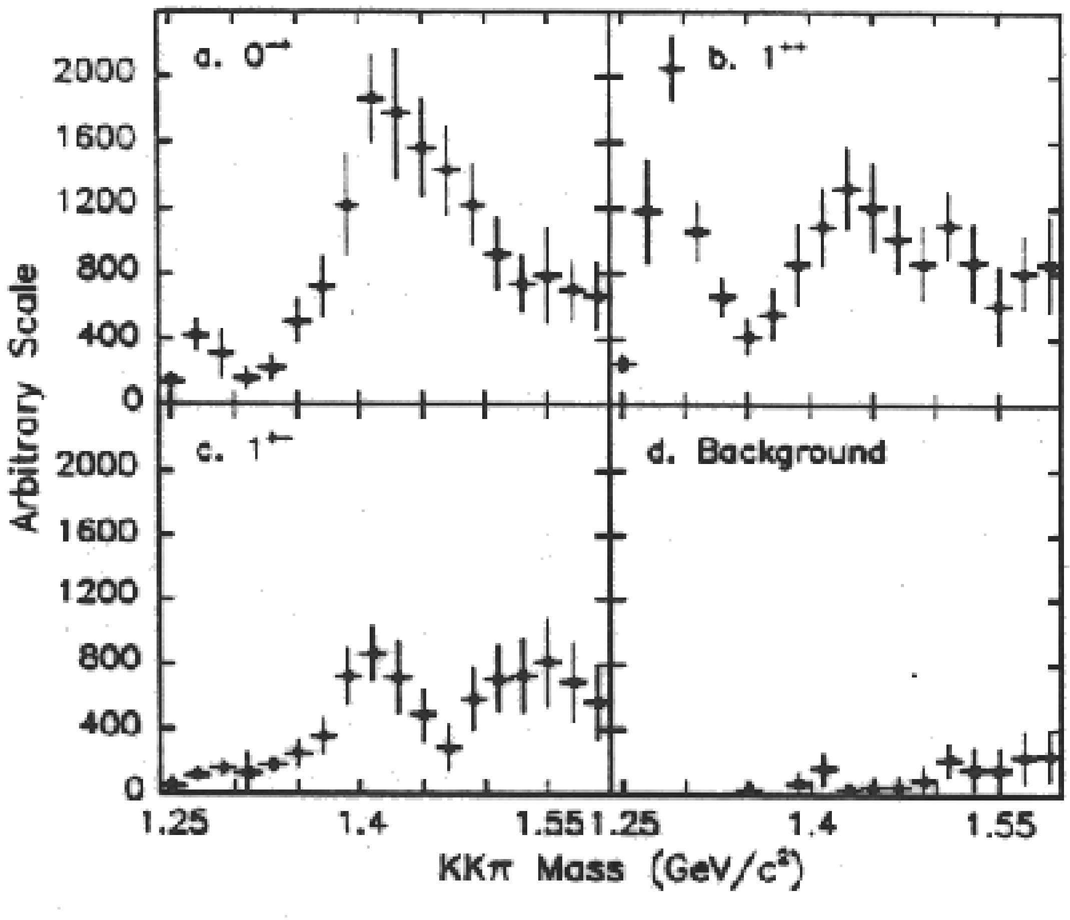


Figure 1



a. 0^{-+}
b. 1^{++}
c. 1^{+-}
d. Background
Arbitrary Scale
0
400
800
1200
1600
2000
1.25
1.4
1.55
KKπ Mass (GeV/c^2)

Figure 2

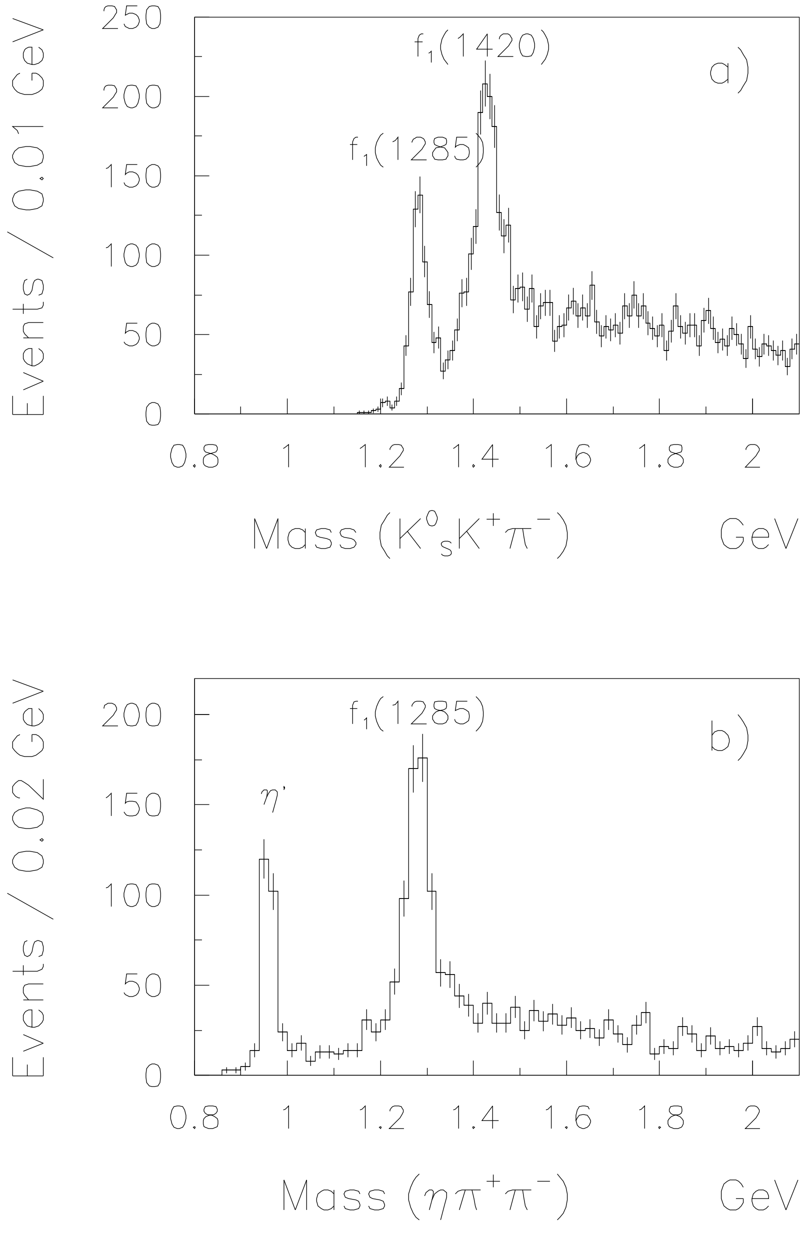

250
200
150
100
50
0
Events / 0.01 GeV
$f_1(1420)$
$f_1(1285)$
a)
0.8
1
1.2
1.4
1.6
1.8
2
Mass ($K^0{}_sK^+\pi^-$)
GeV
200
150
100
50
0
Events / 0.02 GeV
$f_1(1285)$
η'
b)
0.8
1
1.2
1.4
1.6
1.8
2
Mass ($\eta\pi^+\pi^-$)
GeV

Figure 3

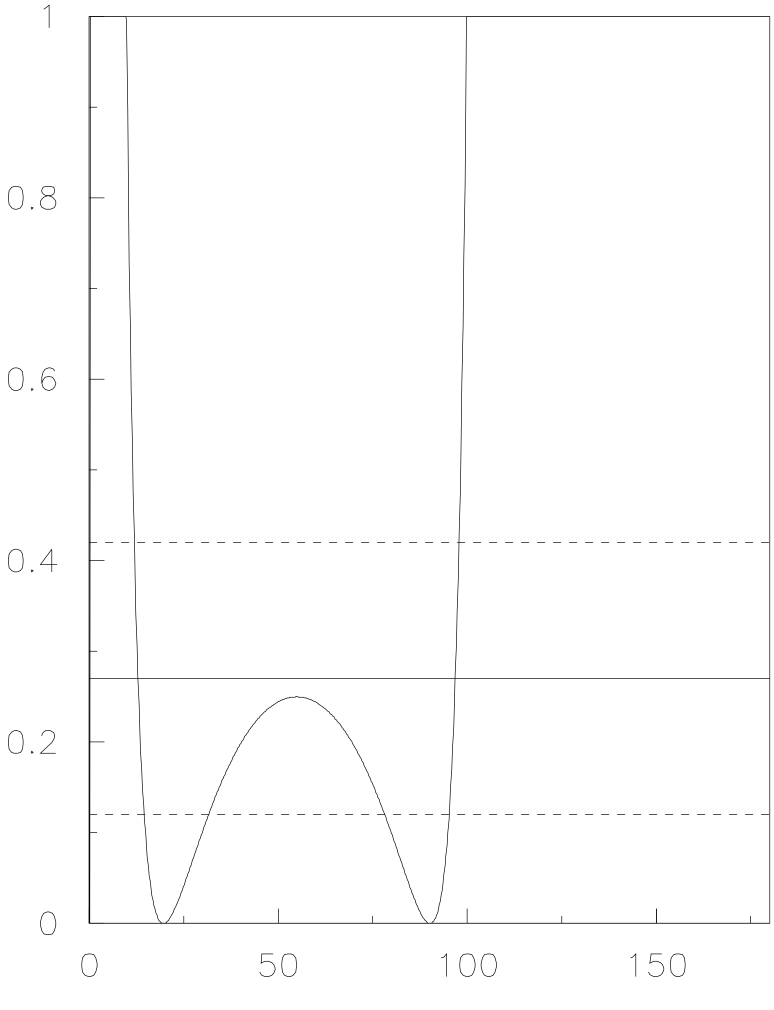
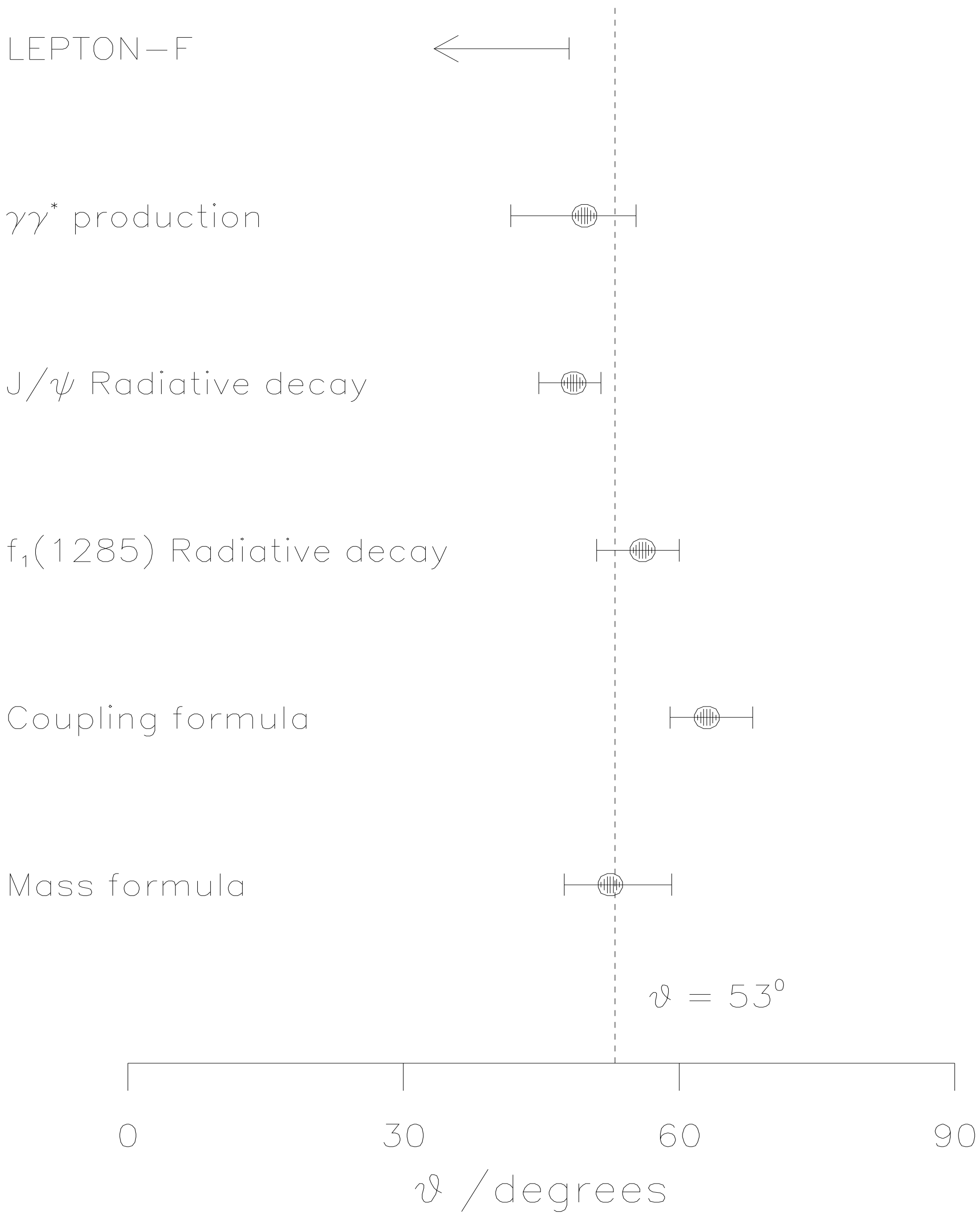


Figure 4



LEPTON−F
$\gamma\gamma^*$ production
J/ψ Radiative decay
$f_1(1285)$ Radiative decay
Coupling formula
Mass formula
$\vartheta = 53^0$
0
30
60
90
ϑ /degrees

Figure 5