Meson Spectroscopy and the Search for Exotics

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Abstract. I will review the current status of exotic hadrons in the meson sector. There is currently strong evidence that a scalar glueball mixed into the normal scalar mesons has been found. There is also an interesting candidate for the tensor glueball state. Finally, I will discuss hybrid mesons with explicitly exotic quantum numbers.

INTRODUCTION

In the context of this paper I will review the current status of exotic mesons; glueballs and hybrid mesons. Our current best evidence for a glueball comes from the scalar meson sector, $J^{PC} = 0^{++}$. In this sector there appears to be two states, the $f_0(1500)$ and $f_0(1750)$ which are produced in several glue–rich mechanisms. The decay rates of the $f_0(1500)$ have been studied in detail by the Crystal Barrel experiment which finds that this state cannot be explained as either a pure glueball nor a pure meson. The $f_0(1500)$ combined with the $f_0(1750)$ leads us to the interpretation that these states are mixtures of both glueball and normal mesons. In the tensor sector, there is currently a very interesting candidate state, the $\xi(2230)$. Its best evidence comes from radiative J/ψ decays, and appears to have several properties suggestive of glueballs. Lastly, there is evidence from E852 at Brookhaven for a state with explicitly exotic quantum numbers. However several properties of this state seem to disagree with expectations for a hybrid meson.

GLUEBALLS

The Theoretical Situation

A pure glueball is a bound state of only gluons. Due to the fact that gluons carry the color charges of QCD, it is theoretically possible for them to form bound states devoid of any quark content. The quantum numbers of these states are derived by considering them to contain either 2 or 3 *valence* gluons. While we are still unable to solve QCD exactly in the nonperturbative regime, most models which are able to explain observed phenomena predict that glueballs should exist, and most predict the lightest will be the scalar, $J^{PC}=0^{++}$. At the moment, we believe that lattice calculations come closest to actually solving non–perturbative QCD. A calculation of the entire glueball spectrum [1] finds that the scalar glueball has a mass of 1550 ± 50MeV/c^2 while the next lightest state is the tensor at a mass of 2270 ± 100MeV/c^2. A recent calculation with a factor of 10 improvement in lattice density predicts that the scalar glueball has a mass of 1740 ± 71MeV/c^2, and for the first time makes predictions for decay rates into flavorless pseudoscalar meson pairs as a function of mass [2]. Given that the two groups have a different procedures to extrapolate to the continuum limit, we take the average of these, $1610\pm70\pm130$ MeV/c^2, as the prediction for the mass of a pure scalar glueball.

Next we consider where we should search for glueballs. There are several reactions which are considered as glue–rich. Radiative J/ψ decays, $\psi\rightarrow\gamma X$ are generally considered the best source of glueballs simply because the c and $\bar{c}$ quark have to annihilate in order for the decay to proceed. Defining $b(R_J\rightarrow xx)=\Gamma(R_J\rightarrow xx)/\Gamma_{\rm tot}$, expectations from [4] give:

$$b(R(\bar{q}q)\rightarrow gg)\simeq 0.1\sim 0.2 \tag{1}$$

$$b(R(G)\rightarrow gg)\simeq 0.5\sim 1. \tag{2}$$

Where equation 1 is for a normal meson and equation 2 is for a glueball. These quantities can be related to the radiative decay rate via equations 3 and 4.

$$(10^3)B(J/\psi\rightarrow\gamma R(0^{++}))=\left(\frac{m}{1500MeV}\right)\left(\frac{\Gamma_{R\rightarrow gg}}{96MeV}\right)\frac{x\mid H_T\mid^2}{35} \tag{3}$$

$$(10^3)B(J/\psi\rightarrow\gamma R(2^{++}))=\left(\frac{m}{1500MeV}\right)\left(\frac{\Gamma_{R\rightarrow gg}}{26MeV}\right)\frac{x\mid H_T\mid^2}{34} \tag{4}$$

In a similar argument, $\bar{p}p$ annihilations are also considered a likely source of glueballs simply because there are so many quarks and antiquarks. It is unfortunately difficult to predict rates, and any signal will be mixed into a background of normal mesons. Finally double pomeron exchange in central production, $pp\rightarrow p_f\mathcal{G}p_S$ is believed to be a likely source of glueballs as the pomeron seems to involve glue. In addition to glue rich sources, there are glue–poor source such as 2γ and photoproduction. There is no direct coupling between the photon and the electrically neutral gluons, so production of glueballs should be suppressed.

Finally, the glueballs are expected to have a decay pattern which in some sense is flavour blind. The gluon couples equally to all flavours of quarks, so the production of u, d and s quarks are expected to be more or less the same. One calculation [3] yields the values in table 1 as the expected relative strengths of for two–pseudoscalar decays. In addition, the 4π decay involving two pairs of $I = 0$ s–wave dipions, $(\pi\pi)_s$ is expected to be a significant and large decay mode of a glueball [5]. This combined with the two–pseudoscalar decays yields the following expectations.

Decay	$\pi\pi$	$\bar{K}K$	$\eta\eta$	$\eta'\eta$	$(\pi\pi)_s(\pi\pi)_s$
Rate	(3)	(4)	(1)	(0)	Large

TABLE 1. Predicted glueball decay rates.

In particular with the scalar glueball there is the problem of the nearby scalar mesons. Excluding the $a_0(980)$ and $f_0(980)$ from consideration, the scalar nonet is presumably made up of the $f_0(1370)$, $a_0(1450)$, $K_0^*(1430)$ and an as yet unidentified f_0' state. The $a_0(1450)$ is a recently identified state with a mass of 1450 ± 40 and width of 270 ± 40 observed in $\bar{p}p$ annihilation at rest and decaying into $\eta\pi$, $\eta'\pi$ and $\bar{K}K$ [6], [7], [8]. Enough of this nonet is known to allow us to make predictions both on the mass and decay rates of the missing f_0' state as a function of the nonet mixing angle. If we find additional scalar states, we should be able to identify they are pure meson or pure glueball.

The Scalar Sector

The Crystal Barrel experiment at LEAR has done a high statistics study of $\bar{p}p$ annihilations at rest into both charged and neutral final states using a nearly 4π solid angle detector for both charged particles and photons. These data have been analyzed in a consistent coupled channel analysis. The analysis is done within the framework of the isobar model using a K–matrix formulation to maintain unitarity and handle multiple decay modes of a given meson [7], [9], [10]. Dalitz plots for several of these final states are shown in figures 1 and 2. In particular, $\bar{p}p \to \pi^\circ\pi^\circ\pi^\circ$ ($\sim 700,000$ events), $\bar{p}p \to \eta\eta\pi^\circ$ ($\sim 200,000$ events) and $\bar{p}p \to K_L K_L \pi^\circ$ ($\sim 50,000$ events) show a new isoscalar scalar state, $((I^G)J^{PC} = (0^+)0^{++})$, the $f_0(1500)$. Its mass and width are found to be $m = 1500 \pm 15\mathrm{MeV/c}^2$ and $\Gamma = 120 \pm 20\mathrm{MeV/c}^2$. In addition to 3–pseudoscalar final states, $\bar{p}p \to \pi^\circ\pi^\circ\pi^\circ\pi^\circ\pi^\circ$ has also been studied [11]. These data show evidence for $f_0(1500) \to (\pi\pi)_s(\pi\pi)_s$. These consistent analyses yield the phase space corrected decay rates for the $f_0(1500)$ as given in table 2.

Using an SU(3) calculation which accurately predicts the relative decay rates for the tensor mesons, we can see if the Crystal Barrel decay rates of the $f_0(1500)$ are consistent with the f_0'. Figure 3 shows the predicted phase space corrected decay rates normalized to the $\eta\eta$ decay rate as a function of the scalar meson mixing angle. The Crystal Barrel data are shown as a horizontal band, and the allowed mixing angles are shown as the shaded

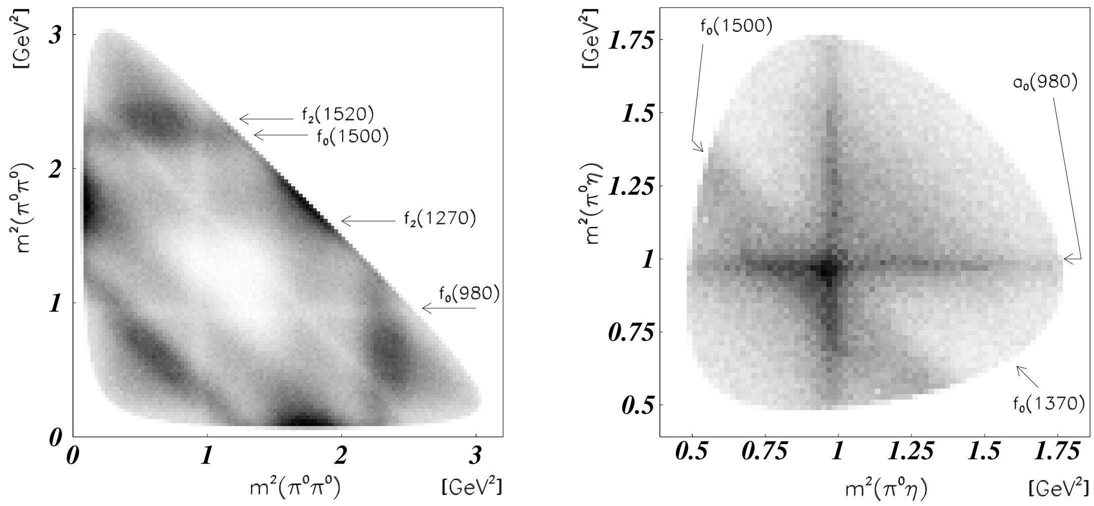

FIGURE 1. The Dalitz plots for $\bar{p}p \to \pi^\circ\pi^\circ\pi^\circ$ (left) and $\pi^\circ\eta\eta$ (right). The $f_0(1500)$ is seen clearly as the band near 2.25 GeV^2 in the $3\pi^\circ$ Dalitz plot. It is also seen as the lower diagonal band in the $\pi^\circ\eta\eta$ Dalitz plot.

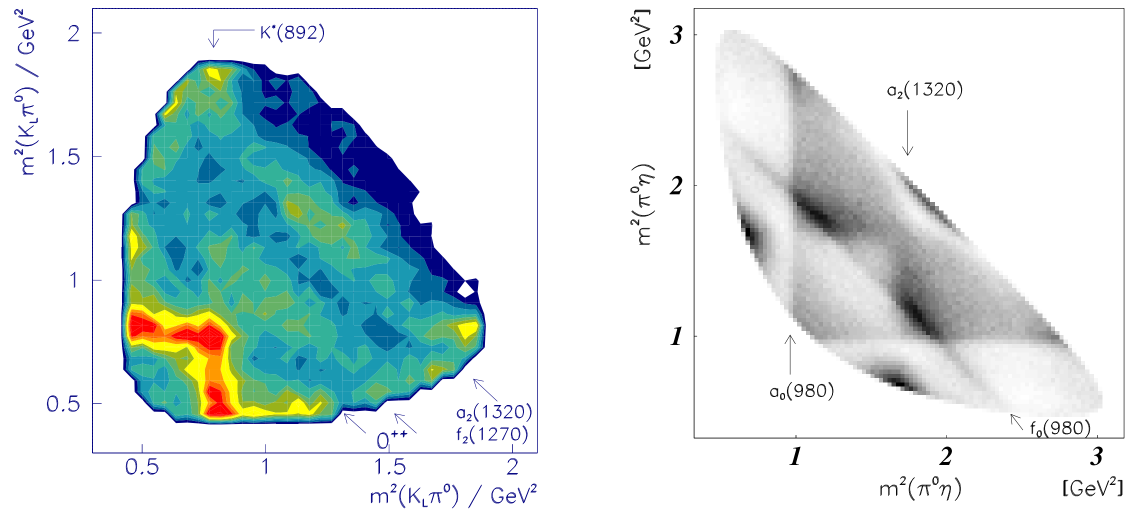

FIGURE 2. The Dalitz plots for $\bar{p}p \to K_L K_L \pi^\circ$ (left) and $\pi^\circ\pi^\circ\eta$ (right). The $f_0(1500)$ is seen labeled as the 0^{++} band in the $K_L K_L \pi^\circ$ Dalitz plot. The $\eta\pi^\circ\pi^\circ$ Dalitz plot is used to constrain amplitudes in other channels.

boxes along the mixing angle axes. From the $\pi\pi$ and $\eta'\eta$ plots, a consistent value of $\theta_s = (68.5 \pm 1.5)^\circ$ is found. Using this value to predict $\bar{K}K$, we find the region shown by the shaded cross, and expect a decay ratio of about 10, nearly 9 times larger than the measured Crystal Barrel Rate. The $f_0(1500)$ cannot be the missing f_0' state. In addition, in table 2 we compare this with the pure glueball. This is also a poor explanation for this object, the $f_0(1500)$ appears to be neither a pure meson nor a pure glueball.

Decay	$\pi\pi$	$\bar{K}K$	$\eta\eta$	$\eta'\eta$	$(\pi\pi)_s(\pi\pi)_s$
$f_0(1500)$	$(4.39 \pm .16)$	$(1.1 \pm .4)$	(1)	$(1.42 \pm .96)$	(14.9 ± 3.2)
GlueBall	(3)	(4)	(1)	(0)	Large
f_0'	(4.4)	(10)	(1)	(2)	

TABLE 2. Measured $f_0(1500)$ decay rates compared to a pure glueball and the expected f_0' state.

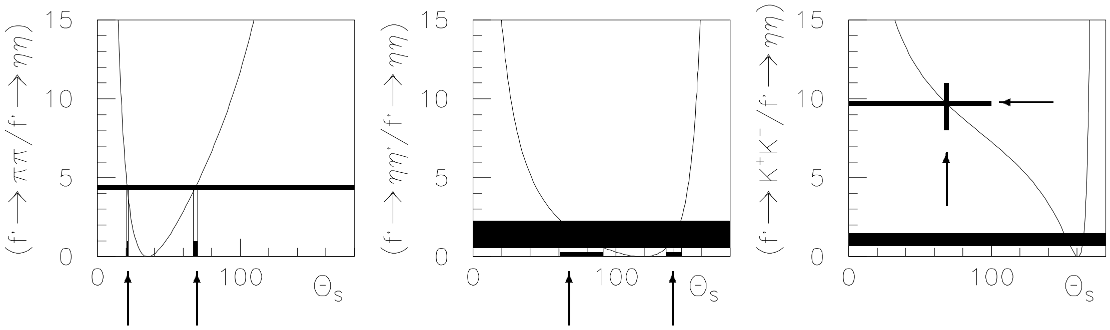

FIGURE 3. Predicted decay rates of the f_0' normalized to $\eta\eta$ as a function of the scalar mixing angle θ_s. The horizontal shaded bands are the Crystal Barrel limits. For $\pi\pi$ and $\eta'\eta$ the allowed values of θ_s are indicated by the arrows. In $\bar{K}K$ the consistent values of θ_s from the previous two (upward pointing arrow) are used to predict a ratio. This is indicated by the left pointing arrow near a ratio of 9.5.

Finally a third scalar state, the $f_0(1750) \to (\pi\pi)_s(\pi\pi)_s$ is hinted at in the $\bar{p}p \to \pi^\circ\pi^\circ\pi^\circ\pi^\circ\pi^\circ$ final state [11]. However, this state is near the edge of available phase space and is so far only observed in the one decay mode. However as we examine radiative J/ψ decays we find that this $f_0(1750)$ is probably the scalar component of the $f_J(1710)$. A reanalysis of MKIII data [12] on $J\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ finds two scalar states both decaying to $(\pi\pi)_s(\pi\pi)_s$. The $f_0(1500)$ and the $f_0(1750)$, ($m = 1750 \pm 15$, $\Gamma = 160 \pm 40$). In addition they find a 2^{++} state at a mass of $1620 \pm 16\mathrm{MeV/c}^2$ and a width $\Gamma = 140^{+60}_{-20}$. These latter two states both come from the $f_J(1710)$ region. They find the radiative decay rates to the scalars as given in 5 and 6.

$$B(J\psi \to \gamma f_0(1500) \to \gamma 4\pi) = (5.7 \pm 0.8) \times 10^{-4} \quad (5)$$
$$B(J\psi \to \gamma f_0(1750) \to \gamma 4\pi) = (9.0 \pm 1.3) \times 10^{-4} \quad (6)$$

Recently, BES has reported both a tensor and scalar state in the $f_J(1710)$ region, $f_2(1690)$ ($m = 1696 \pm 5^{+9}_{-34}$, $\Gamma = 103 \pm 8^{+10}_{-31}$) and $f_0(1780)$ ($m =$

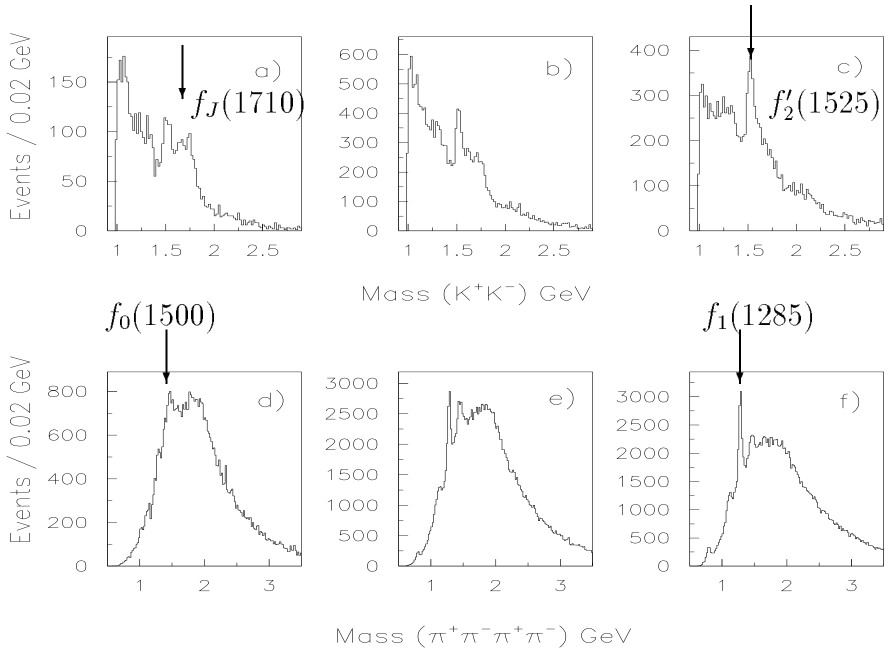

FIGURE 4. (**a**,**d**) $dP_T < 0.2$, (**b**,**e**) $0.2 < dP_T 0.5$ and (**c**,**f**) $dP_T > 0.5$, (see text).

$1781 \pm 8^{+10}_{-31}$, $\Gamma = 85 \pm 24^{+22}_{-19}$), both decaying to $\bar{K}K$ [13]. These are presumably the same states as seen in MKIII, and we will adopt the name $f_0(1750)$ for the scalar state. At this conference, BES reported on radiative decays to four pions [14]. They find the results; and 8.

$$B(J\psi \rightarrow \gamma f_0(1500) \rightarrow \gamma 4\pi) = (4.0 \pm 0.6) \times 10^{-4} \quad (7)$$
$$B(J\psi \rightarrow \gamma f_0(1750) \rightarrow \gamma 4\pi) = (5.5 \pm 0.8) \times 10^{-4} \quad (8)$$

Taking these together with the fact that 4π is on order of 50% of the decay rate, one finds using equations 3 and 4 that

$$b(f_0(1500) \rightarrow gg) \simeq 0.5 \sim 0.8$$
$$b(f_0(1750) \rightarrow gg) \simeq 0.5.$$

Both of which are highly suggestive of a large gluonic content in the states [5].

Finally, we examine data from central production — $pp \rightarrow p_f(X)p_s$. Both the $f_0(1500)$ and the $f_J(1710)$ have been reported in central production. However a recent observation made by the WA91 and WA102 collaborations [15] yields an interesting separation of normal mesons from the exotic candidates. In central production, double pomeron exchange is believed to be responsible for formation of gluonic states. However, normal mesons are also produced, and separation of these has always been difficult. If we consider the transverse momentum transfer from each proton as P_{T1} and P_{T2}, and the beam axis along z, one can define a variable

$$dP_T = \sqrt{(P_{x1} - P_{x2})^2 + (P_{y1} - P_{y2})^2}. \qquad (9)$$

In a sense, this is the difference in transverse momentum between the two pomerons. When this quantity is small one could visualize the two pomerons as traveling together, while when this is large, they are moving apart. Data for $(X) = (K^+K^-)$ and $(\pi^+\pi^-\pi^+\pi^-)$ are shown in figure 4. The interesting feature is that for large dP_T, (**c** and **f**), K^+K^- shows a clear signal for the $f_2'(1525)$ and 4π shows a clear signal for the $f_1(1285)$ — both of which are normal mesons. However in the small dP_T region, (**a** and **d**) both of the previous states are gone and the $f_0(1500)$ and $f_J(1710)$ appear. Having the pomerons moving *together* enhances the exotic candidates, while having them move *apart* enhances the normal mesons.

These three production mechanisms taken together lead one to the conclusion that both the $f_0(1500)$ and the $f_0(1750)$ have a large gluonic component. Given that these are near the scalar mesons, one interpretation is that the pure f_0, f_0' and $\mathcal{G}$ states have mixed and become the observed $f_0(1370)$, $f_0(1500)$ and $f_0(1750)$ states. Two mixing schemes have been proposed to explain this. A lattice inspired mixing based on computed masses [16] and a more data inspired approach [5]. Both of these claim to explain the measured decay rates of the $f_0(1500)$ state and are quite similar in their predictions. At this point it seems we have very strong evidence for a scalar glueball state mixed into the scalar nonet, and the question is now down to details of mixing.

The Tensor Sector

Assuming we have found the scalar glueball near the lattice predictions, we also can ask about the next state, the tensor glueball. Here the information is not nearly as clear, but a new candidate, the $\xi(2230)$ or $f_J(2230)$ has reemerged in recent years due to new measurements from BES [17]. This state has a mass of 2230 and an extremely narrow width of 20. In addition, its decays appear nearly flavour–blind over $\pi\pi$, $\bar{K}K$ and $\bar{p}p$. It also appears to have a rather large rate for $J/\psi \rightarrow \gamma\xi$ which would be indicative of a large gluonic component. However it's spin is currently unclear — being either 2^{++} or 4^{++}. Even though it has been reported by BES to decay to $\bar{p}p$, this state has not been observed in $\bar{p}p$ direct production. Dave Hertzog [18] has given a nice summary of the results and consequences of this at this conference. The current situation is that these measurements are just barely compatible, but as the $\bar{p}p$ limits improve, this may change. In addition, this state has been searched for and not observed in two–photon production [19]. Its nonobservation lends support to the glueball interpretation if this state is indeed a tensor. Finally, BES has recently reported the observation of 4π decays of a state $f_2(2220)$ [14]. They find a spin 2 state at a mass of $m = 2220$ and a width of $\Gamma = 105^{+70}_{-50}$ decaying to $f_2(1270)(\pi\pi)_s$. While the width is larger than that observed for the $\xi(2230)$, if they are the same state it is a measurement of the spin. In addition, they find a radiative rate of $B(J/\psi \rightarrow \gamma f_2 \rightarrow \gamma 4\pi) = (2.6 \times 10^{-4})$.

HYBRIDS

Hybrids are meson–like states to which a valence gluon has been added. The quantum numbers of these states are given by those of the underlying meson plus the quantum numers of the gluon. These states are predicted in several models, and are expected to appear in nonets. In the *fluxtube* model of Isgur and Paton [20] one expects 8 nonets with quantum numbers $\underline{0^{+-}}$, 0^{-+}, 1^{++}, 1^{+-}, $\underline{1^{-+}}$, 1^{--}, $\underline{2^{+-}}$ and 2^{-+}. What makes these states intriguing is that the underlined quantum numbers are not possible for a $\bar{q}q$ pair. Observation of a state with these quantum numbers would be a *smoking gun* for a non–$\bar{q}q$ state. The masses of the lightest hybrid mesons are expected to be in the 1700 to 1900 MeV/c^2 mass range, and an additional signature is that they are expected to decay into a pair of P and S wave mesons, *e.g.* $f_1(1285)\pi$, $a_2(1320)\pi$, *etc.* whereas final states like $\eta\pi$ and $\pi\pi$ should be suppressed. In addition, the hybrids with $\bar{q}q$ quantum numbers might very well mix with their normal meson counterpart. A recent calculation of the decays of all mesons and hybrids [21] withing the framework of the fluxtube model will provide a guide to interpreting these states, but we need to observe a state with non–$\bar{q}q$ quantum numbers to prove the existence of hybrids.

At this conference, Brookhaven E852 has presented evidence for a 1^{-+} state decaying into $\eta\pi$ [22]. This state, the $\pi_1(1370)$ is observed in the reaction $\pi^- p \rightarrow \eta\pi^- p$ at 18GeV/c. The state appears from a detailed partial wave analysis, and is seen via its interference with the much stronger $a_2(1320)$ state. The data are most easily explained by the introduction of a resonant state with a mass $m = 1370 \pm 16^{+50}_{-30}$ and a width of $\Gamma = 385 \pm 40^{+65}_{-105}$. In figure 5 are shown the results of their partial wave analysis. The results yields 8 possible solutions, and the ranges of each value are shown as solid vertical bars for the fits. **a** shows the D_+ wave which corresponds to the strong $a_2(1320)$, while in **b** is the resulting amplitude of the P_+ partial wave as a function of $\pi\eta$ mass. The amplitude peaks near 1370, and is about 3% of the strength of the D_+ wave. In **c** is shown the fit phase difference between the two waves. In order to explain this, they postulate that a resonant state, the $\pi_1(1370)$ is produced in addition to the $a_2(1320)$. They allow a relative production phase between these and treat both states as Breit–Wigner resonances. This hypothesis is able to reproduce the data, and yields the 4 phases shown in **d** with the relative production constant over the $\pi\eta$ invariant mass. Their data agree quite well with earlier data from VES in the reaction $\pi^- N \rightarrow \eta\pi^- N$ at 37Gev/c. In particular the same phase difference is observed in both data sets.

While there does appear to be something here, it's interpretation is not so

FIGURE 5. **a** Data and fit for the D_+ wave showing a strong $a_2(1320)$. **b** Data and fits for the P_+ partial wave. **c** Relative phase between the D_+ and P_+ partial waves. **d** (1) Phase of the D_+, (2) P_+, (3) difference and (4) production.

clear. The mass seems too low to be the hybrid meson predicted by the flux tube model, and the decay mode is also not favored. If it is a hybrid meson, then we expect it to be a member of a nonet. In particular we expect to find both an η_1 and an η_1' state. Depending on their masses, likely decay modes would be either $\eta\eta'$ or $a_1(1260)\pi$. The latter would be particularly difficult to extract from data, but its observation may be quite important as establishing this state as a hybrid meson.

CONCLUSIONS

The scalar meson sector shows strong evidence for a glueball mixed into the normal mesons. Two states, $f_0(1500)$ and $f_0(1750)$ have both been observed in three glue–rich mechanisms. In radiative J/ψ decays, their large rates are indicative of a large gluonic content. In central production, both states stand out from normal mesons via the dP_T in equation 9. Finally, in $\bar{p}p$ annihilation, the relative decay rates of the $f_0(1500)$ have been measured and lead one to the conclusion that the state is neither a pure meson nor a pure glueball. The simplest explanation for what we observe is that the three observed scalars, $f_0(1370)$, $f_0(1500)$ and $f_0(1750)$ are the result of mixing between the pure f_0 and f_0' with the scalar glueball $\mathcal{G}$. In the tensor sector, we have a rather interesting candidate, the $\xi(2230)$. This state is observed in radiative J/ψ decays with a rate suggestive of a large gluonic content, has a very narrow width $\Gamma \sim 20$MeV and seems to have flavor blind decays. While more details are needed, this does appear as our best candidate for the tensor glueball.

Finally, we have evidence for a state with exotic quantum numbers, $\pi_1(1370)$ observed in $\pi^- p \to \eta\pi^- p$. The state is consistent between two different $\pi^- N$ experiments, but its interpretation is murky. Its mass is much lower than one expects for a hybrid meson, but observation of one of its partners could help clarify this.

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