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EXPERIMENTAL INDICATIONS FOR A 2^{++} NON- $\bar{q}q$ OBJECT

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ABSTRACT

Using our high statistics data from the $\pi p \rightarrow \pi\pi n$ reaction, we have remade a model-independent partial wave analysis in finer mass bins at low four-momentum transfer. The Breit-Wigner fits to the leading waves yield $m_\rho = (777.4 \pm 2.0)$ MeV and $\Gamma_\rho = (160 \begin{smallmatrix} + 4.1 \\ - 4.0 \end{smallmatrix})$ MeV, as well as $m_f = 1273 \pm 2.3$ MeV, $\Gamma_f = (179.2 \begin{smallmatrix} + 6.9 \\ - 6.6 \end{smallmatrix})$ MeV and $x_f = (84.9 \pm 2.5)\%$. The last two parameters yield $\Gamma(f \rightarrow \pi\pi) = (152.1 \pm 7.3)$ MeV, a value which is higher than the one resulting from fits to the decays of the $J^{PC} = 2^{++}$ mesons. On the basis of a smaller discrepancy, Rosner has speculated about a non- $q\bar{q}$ admixture (possibly gg) in the $f(1270)$, i.e. $|f(1270)\rangle = |q\bar{q}\rangle \cos \theta + |gg\rangle \sin \theta$. Repeating his fits with more recent data we obtain a considerably more significant effect with $\sin^2 \theta = 0.21 \pm 0.05$. This sets a mass of an orthogonal state $|f_T\rangle = -|q\bar{q}\rangle \sin \theta + |gg\rangle \cos \theta$ between 1420 and 1600 MeV. The f_T could be identified with a 1440 MeV state seen in some $\bar{K}K$ experiments, A_1 exchange being a possible production mechanism. A fit to our polarized target K^+K^- data at ~ 18 GeV/c yields $m(f_T) = (1436 \begin{smallmatrix} + 26 \\ - 16 \end{smallmatrix})$ MeV and $\Gamma(f_T) = (81 \begin{smallmatrix} + 51 \\ - 29 \end{smallmatrix})$ MeV.

1. INTRODUCTION

In previous papers [1,2] we have reported the results of a model-independent partial wave analysis of the reaction

$$\pi^- p \rightarrow \pi^+ \pi^- n \quad (1)$$

at 17.2 GeV/c. The analysis covering the mass range from 600 to 1800 MeV in 40 MeV bins yielded unique solutions for all partial waves (except for an up-down ambiguity in the S-wave). Thus having ambiguities well under control we have repeated the analysis in finer mass bins. This is described in section 2. The results allow more accurate determination of the parameters of $\rho(770)$ and $f(1270)$ resonances and this is described in section 3.

Of particular interest is the large value of $\Gamma(f \rightarrow \pi\pi)$. Recently Rosner [3] suggested that this might be due to a non- $q\bar{q}$ admixture in the $f(1270)$. In section 4 we repeat his SU(3) and/or SU(6) fits to the decay widths of $J^{PC} = 2^{++}$ mesons using more recent data. They allow us to fix the range of the mass of another $J^{PC} = 2^{++}$ meson f_T , which is "orthogonal" to the ordinary $f(1270)$. Using this mass and other parameters of f_T as predicted by Rosner we try to identify f_T with a ~ 1440 MeV state possibly seen or even claimed in some studies of the reactions

$$\pi^- p \rightarrow K^+ K^- n \quad (2)$$

$$\pi^- p \rightarrow K_S^0 K_S^0 n . \quad (3)$$

This is described in section 5, while in section 6 we discuss a possible production mechanism of the $f_T(1440)$ in reactions (2) and (3) and try to determine its parameters from our data at ~ 18 GeV/c.

2. PARTIAL WAVE ANALYSIS

Since the present analysis follows exactly our study of reaction (1) in refs. [1,2] as well as that of reaction (2) in ref. [4], we will only recall here the main features of such an analysis. A most extensive description is given in ref. [5].

The most general formula for the differential cross-section in reaction (1) on a transversely polarized target is

$$\begin{aligned} \frac{d^2\sigma}{dm dt d\Omega} = & \sum_{L,M} t_M^L(m_{\pi\pi}, t) \operatorname{Re} Y_M^L(\Omega) + P \cos \psi \sum_{L,M} p_M^L(m_{\pi\pi}, t) \operatorname{Re} Y_M^L(\Omega) + \\ & + P \sin \psi \sum_{L,M} r_M^L(m_{\pi\pi}, t) \operatorname{Im} Y_M^L(\Omega), \end{aligned}$$

where

- $m_{\pi\pi}$: effective mass of the $\pi\pi$ system
- t : four-momentum transfer from the beam particle to the $\pi\pi$ system
- Ω : decay angles of the π^- in the t-channel $\pi\pi$ rest frame
- ψ : polarization angle
- P : degree of polarization
- $\left. \begin{array}{l} t_M^L \\ p_M^L \\ r_M^L \end{array} \right\}$: moments of the angular distribution
(bilinear combinations of partial wave amplitudes)

Experiments without polarized targets measure only the first term (t_M^L moments) and the number of observables is smaller than the number of unknown parameters. In such a case a partial wave analysis is impossible without model assumptions (usually π exchange is assumed to dominate).

In our analysis we use both 3×10^5 events of reaction (1) on a hydrogen target [6] and 1.2×10^6 events on a polarized (butanol) target [1,2] at 17.2 GeV/c. The former yields t_M^L moments, while the latter provides the p_M^L and r_M^L moments from interactions with the protons of hydrogen bound in the butanol molecule (the protons in nuclei cannot be polarized). In such a way we could perform a model-independent partial wave analysis. In particular, the partial wave intensities could be determined without any *a priori* physical assumptions. This was done in 40 MeV mass bins for $600 \text{ MeV} < m_{\pi\pi} < 1780 \text{ MeV}$ and for $0.01 \text{ GeV}^2/c^2 < -t < 0.20 \text{ GeV}^2/c^2$.

In the present analysis we have used finer mass bins ($\Delta m = 20$ MeV) and slightly different kinematical regions, i.e.

$$\begin{aligned} 600 \text{ MeV} < m_{\pi\pi} < 1560 \text{ MeV} \\ 0.005 \text{ GeV}^2/c^2 < -t < 0.20 \text{ GeV}^2/c^2 . \end{aligned}$$

The upper limit of the mass range has been lowered, since owing to the low acceptance at high mass we cannot determine the parameters of the $g(1700)$ anyway. This allowed us to extend the four-momentum transfer range down to $0.005 \text{ GeV}^2/c^2$, still above the kinematical limit $t_{\min}$ for the whole mass range. As in refs. [1,2] we have performed an energy-independent analysis, i.e. each mass bin has been fitted independently of its neighbours. We have divided our mass range into three regions depending on the maximum ℓ (spin of the $\pi\pi$ system), the limits between regions being determined empirically. Below 980 MeV the D-waves ($\ell \geq 2$) are not needed, while below 1380 MeV the F-waves ($\ell \geq 3$) can be neglected. It is seen in fig. 1 that the solutions are unique and fairly smooth except in two regions. The first is an up-down ambiguity in the S-wave, the second is around 1450 MeV. In the following section we will show that the solution 1 (higher D-wave) is preferred by demanding a single $f(1270)$ resonance.

3. BREIT-WIGNER FITS TO THE P_0 - and D_0 -WAVES

We fit the intensities of the leading waves ($\pi\pi$ helicity $m = 0$) by the formula

$$|L_0|^2 = A \frac{m_{\pi\pi}^2}{q} \left| \frac{\sqrt{2\ell+1} m_R x_R \Gamma}{m_R^2 - m_{\pi\pi}^2 - i m_R \Gamma} \right|^2 ,$$

where

$$\Gamma = \Gamma_R \left(\frac{q}{q_R} \right)^{2\ell+1} \frac{D_\ell(q_R)}{D_\ell(q_R)}$$

$$D_1(q_R) = 1 + (q_R)^2$$

$$D_2(q_R) = 9 + 3(q_R)^2 + (q_R)^4$$

A : overall normalization constant

m_R, Γ_R, x_R : mass, width, and elasticity of the resonance R ($R = \rho, f$), respectively

q : momentum of one of the pions in the $\pi\pi$ rest system

q_R : $q(m_{\pi\pi} = m_R)$

R : range parameter of the order of $5-10 \text{ GeV}^{-1}$.

For the D_0 -wave we include the small component of the isospin $I = 2$, using the results of ref. [7]. The results of our fits are shown in table 1.

The solution 2 with the D_0 -wave falling nearly to zero at 1450 MeV cannot be fitted by a single resonance and produces a completely unknown second object strongly coupling to $\pi\pi$ when fitted by two resonances.

The $\rho(770)$ resonance is quite insensitive to the up-down ambiguity in the S-wave. These results as well as the single resonance fit to the D_0 -wave are also independent of the mass range used and we treat them as the best estimates from our experiments.

Obviously the values from table 1 supersede the previous ones obtained in 40 MeV bins in a more restricted t range [1], while being entirely consistent with them. We comment here on the error in the $f(1270)$ elasticity. From the fit to $f(1270)$ we obtain $\Delta x = 1.3\%$. We assume a purely elastic $\rho(770)$ in order to fix the normalization constant A . This constant is then used to determine the $f(1270)$ elasticity. Adding ΔA from the $\rho(770)$ to Δx from the $f(1270)$ fit leads to $\Delta x_f = 2.5\%$.

4. A POSSIBILITY OF A NON- $\bar{q}q$ ADMIXTURE IN THE $f(1270)$

In this section we follow the analysis of Rosner [4]. His starting point was the observation that the decay width $\Gamma(f \rightarrow \pi\pi) = (148 \pm 17) \text{ MeV}$ (calculated from the data in the 1980 edition of the Particle Data Group [8]) is larger than the value resulting from the $SU(3)$ and/or $SU(6)$ fits to the other decays of $J^{PC} = 2^{++}$ mesons. As a possible explanation for this discrepancy he assumes that the "ordinary" $f(1270)$ is an admixture of a "normal" $q\bar{q}$ and a gluonium gg component.

$$|f\rangle = \cos \theta |q\bar{q}\rangle + \sin \theta |gg\rangle .$$

Its orthogonal partner

$$|f_T\rangle = -\sin \theta |q\bar{q}\rangle + \cos \theta |gg\rangle$$

is assumed to be completely decoupled from the $\pi\pi$ channel. Rosner's conjecture introduces an additional mixing parameter θ into the decay of $f(1270)$. From the SU(3) fits to the $2^{++} \rightarrow 0^{-}0^{-}$ decays [$f(1270) \rightarrow \pi\pi$, $f(1270) \rightarrow \bar{K}K$, $A_2(1310) \rightarrow \bar{K}K$ and $K(1430) \rightarrow K\pi$] and the SU(6) fits to the $2^{++} \rightarrow 0^{-}1^{-}$ decays [$A_2(1310) \rightarrow \rho\pi$, $K(1430) \rightarrow K(890)\pi$] Rosner has found

$$\sin^2 \theta = 0.15 \begin{array}{c} + 0.05 \\ - 0.06 \end{array}$$

i.e. only a 2.5 standard deviation effect. This error corresponds to a large uncertainty in the mass of the "orthogonal" f_T , i.e.

$$1450 \text{ MeV} < m_T < 1850 \text{ MeV} .$$

But now we claim to have a much better estimate of the basic parameter $\Gamma(f \rightarrow \pi\pi) = x_f \Gamma_f = (152.1 \pm 7.3) \text{ MeV}$ from the fit to solution 1. Before repeating the fits of Rosner we have critically reviewed all the decay widths used by him and we have changed two of them.

Since the 1980 edition of the Review of Particle Properties, more data have been on the $(f \rightarrow \bar{K}K)/(f \rightarrow \pi\pi)$ branching ratio. In table 2 we have listed all the high-statistics experiments known to us.

It is seen immediately that the value of 3.3% quoted in ref. [8] is too low. The weighted average from the results listed in table 2 is 4.0%. This is fairly important because a bigger branching ratio would yield larger values of θ . But table 2 also suggests a systematic difference between K^+K^- and K^0K^0 results. It is easier to disentangle $f(1270)$ from the $K_S^0K_S^0$ data because Bose statistics reduces the number of partial waves. On the other hand, the K^+K^- results come from experiments with higher statistics. In addition to that, the $\pi\pi$ data obtained in the same apparatus at the same (or very similar) energy were used, whereas in the analysis of the K^0K^0 experiments the $\pi\pi$ data obtained in other experiments are extrapolated to the $K_S^0K_S^0$ energy. In this situation we have averaged $K_S^0K_S^0$ and K^+K^- experiments separately and used the mean value of these two sets, the error being half of the difference between the averages. This procedure described in

ref. [8] yields $(4.04 \pm 0.62)\%$, which corresponds to $\Gamma(f \rightarrow \bar{K}K) = (6.1 \pm 1.0) \text{ MeV}$ compared to $(5.0 \pm 0.8) \text{ MeV}$ used by Rosner.

The other change has been made for $\Gamma(A_2 \rightarrow \bar{K}K)$, where we have taken $(A_2 \rightarrow \bar{K}K)/(A_2 \rightarrow \rho\pi) = (7.75 \pm 1.7)\%$ from the CERN-Munich paper [14]. The reason was that this value comes from a fit to all the results available at that time so that the averaging in ref. [8] is a double counting. Thus we have used $\Gamma(A_2 \rightarrow \bar{K}K) = (5.5 \pm 1.2) \text{ MeV}$ resulting from ref. [14] and a total width of $A_2(1310)$.

The rest of the experimental decay widths and the whole fitting procedure is the same as in Rosner's paper. Our results are listed in table 3. Comparing our results with those from the original fit made by Rosner (quoted in brackets) we see that our SU(3) fit is better and yields higher $\sin^2 \theta$ owing to larger $\Gamma(f \rightarrow \bar{K}K)$ and a smaller error in $\Gamma(f \rightarrow \pi\pi)$. This smaller error leads also to better determination of $\sin^2 \theta$ in our SU(6) fit. We observe a much stronger deviation from $\sin^2 \theta = 0$ than Rosner. This, we believe, considerably strengthens his conclusions.

Using $\sin^2 \theta = 0.21 \pm 0.05$ and assuming that a $\bar{q}q$ non-strange isoscalar member of a 2^{++} nonet is at the $A_2(1310)$ mass we have repeated Rosner's calculation and obtained

$$m(f_T) = m(A_2) + [m(A_2) - m(f)] \cot^2 \theta = (1420-1600) \text{ MeV} ,$$

which suggests that the $|gg\rangle$ mass is between 1380 and 1540 MeV, and is not far from the QCD predictions (see ref. [3] for an extensive reference list).

It should also be mentioned that according to Donoghue [15] such a simple mixing scheme, which does not include the $f'(1515)$, might be too naïve. Nevertheless, we try to take the prediction of the new state f_T seriously and to look for it in the data known to us. Hereafter we will use the name of $f_T(1440)$, anticipating the results of fits made in Section 6.

5. A POSSIBLE OBSERVATION OF $f_T(1440)$ IN THE $\bar{K}K$ DECAY CHANNEL

In this section we will discuss a possible direct observation of the $f_T(1440)$ in hadronic reactions. Let us first recapitulate its hypothetical features following Rosner:

- i) mass between 1400 and 1550 MeV,
- ii) decoupling from $\pi\pi$ but coupling to $\bar{K}K$ and 4π roughly as strongly as ordinary $f(1270)$,
- iii) relatively small width of the order of 40 MeV [this is a consequence of (ii)].

Thus we can expect to see the $f_T(1440)$ either in the 4π or in the $\bar{K}K$ channel. In the 4π channel even such a strong resonance as $f(1270)$, produced by π exchange, is but a small effect on a huge background. Nevertheless it might be worthwhile to mention that in the two experiments with the highest statistics [16,17] the shape of $f(1270) \rightarrow 4\pi$ is seriously distorted with a dip at 1350 MeV. Unfortunately the large background and the possibility of interference with $D(1285)$ makes any definite conclusions about the $f_T(1440)$ hardly possible.

Thus only the $\bar{K}K$ channel is left. This immediately raises a problem of interference with $f(1270)$, with $A_2(1310)$, and especially with an $f'(1515)$ which should be disturbed by a nearby $f_T(1440)$. This effect should be fairly weak in K-induced reactions, i.e.

$$K^- p \rightarrow K^+ K^- \Lambda(\Sigma) \quad (4)$$

$$K^- p \rightarrow K_S^0 K_S^0 \Lambda, \quad (5)$$

since $f_T(1440) \rightarrow \bar{K}K$ coupling is much smaller than the $f'(1515) \rightarrow KK$. On the other hand, in π -induced reactions $f'(1515)$ production is strongly suppressed by the Okubo-Zweig-Izuka (OZI) rule so here $f_T(1440)$ could be relatively stronger and considerable interference effects are expected. This can explain the systematic difference between the $f'(1515)$ parameters determined in both reactions as seen in table 4. For the highest-statistics data taken at 6 GeV/c [9] we quote both the original results (in brackets) and the results obtained with correct parametrization in ref. [10].

It was argued in refs. [9] and [10] that this difference may be due to neglecting an interference with $f(1270)$ and $A_2(1310)$ in K-induced reactions. We think this unlikely since these resonances as well as the hypothetical $f_T(1440)$ couple only weakly to the $\bar{K}K$ channel as compared to $f'(1515)$. This is well demonstrated in recent high statistics studies [20,22] of $f'(1515)$. A very clean $f'(1515)$ peak seen in these experiments shows that there is little or no interference in K-induced reactions. In our opinion it is in π -induced reactions that all the interferences might be important. Therefore the true parameters of the $f'(1515)$ should be determined from reactions (4) and (5) only. This yields

$$m(f') = (1524 \pm 3) \text{ MeV}$$

$$\Gamma(f') = (74 \pm 7) \text{ MeV}$$

(note the small errors resulting from the good consistency of all measurements).

It should be stressed here that a possibility of a fourth D-wave resonance has been explicitly discussed in the CERN-Cracow-Munich paper [10] studying reaction (2) at $\sim 18 \text{ GeV}/c$. It has been found that the t_0^4 moment (mainly proportional to $|D_0|^2$) needs a fourth D-wave object if the mass and width of $f'(1515)$ are fixed at the values given in the table. The parameters of this fourth resonance are $m = (1422 \pm 9) \text{ MeV}$ and $\Gamma = (80 \pm 42) \text{ MeV}$, which agree quite well with the expected values for $f_T(1440)$ listed at the beginning of this section. It was concluded in ref. [10] "that such an object does not easily fit into the quark-antiquark scheme" and we believe that the $f_T(1440)$ suggested by Rosner would provide a natural explanation of this object.

An indication for such an object can also be seen in reactions (2) and (3) at $62 \text{ GeV}/c$ [23] and in reaction (3) at $23 \text{ GeV}/c$ [13], but they do not represent conclusive evidence.

6. ON THE PRODUCTION MECHANISM OF THE $f_T(1440)$

A possible observation of $f_T(1440)$ in π -induced reactions immediately raises the question about its production mechanism, since the usually dominant π -exchange is forbidden here. A natural spin-parity exchange suggested by Rosner seems to be

excluded by some results at 18 GeV/c [10], namely the high four-momentum transfer data ($0.2 < -t < 1.0 \text{ GeV}^2/c^2$), where the π -exchange is expected to be relatively weaker. Both $L = 4$ moments and D-wave intensities obtained in a model-independent way [5] (see fig. 2) show that in the natural exchange (t_2^4 and D_N) there is no effect in the $f_T(1440)$ region, while $f(1270)$ and/or $A_2(1310)$ dominate more clearly than at low $|t|$. On the other hand, it is the D_0 -wave (t_0^4 and t_1^4 moments) which peaks around 1400 MeV.

This leaves A_1 exchange as a possible production mechanism of $f_T(1440)$ in reaction (2). Such an exchange would be reflected in the polarization dependent moments for this reaction. Let us remember that these moments are generally consistent with zero, which is not the case in reaction (1). For the $\pi\pi$ system it is the simultaneous presence of the $f(1270)$ production by π -exchange (spin flip) and A_1 -exchange (non-spin flip) which yields polarization effects. In the K^+K^- channel more resonances are seen [9,10]: strong $f'(1515)$ with a similar production mechanism to that of $f(1270)$, weak $A_2(1310)$ probably mainly in the non-spin-flip amplitude (Z_0 exchange), and possibly $f_T(1440)$ produced exclusively by A_1 exchange. A complicated interplay of these four objects could lead to a considerably weaker polarization effect.

In order to illustrate this statement we have repeated the fits to reaction (2) made in ref. [10] by fitting now simultaneously the unnormalized t_0^4 moment from 18.4 GeV/c data on hydrogen and a p_0^4 moment from 17.2 GeV/c on butanol (they were normalized to the same energy assuming a p_{lab}^{-2} dependence). The following parametrization has been used

$$t_0^4 \propto \frac{m_{KK}^2}{q} (|D_0^n|^2 + |D_0^f|^2 + \text{const } |F_0|^2)$$

$$p_0^4 \propto \frac{m_{KK}^2}{q} \text{Im } D_0^n D_0^{f*}.$$

The F_0 -wave is described by the Breit-Wigner formula for the $g(1700)$. It does not contribute to p_0^4 since we have not seen any significant polarization effect for this wave in the reaction (1). Other simplifications implicit in the above formulae, i.e.

$$\begin{aligned} |D_U|^2 &\propto |D_0|^2 \\ |D_N|^2 &\propto |D_0|^2 \\ \text{Re } P_0 F_0^* &\ll |D_0|^2 \end{aligned}$$

are seen to be reasonably well satisfied in the model-independent analysis of ref. [4]. The spin-flip D_0^f -wave is assumed to be described by

$$D_0^f = 0.94 |c_f \text{BW}(f) + c_{f'} e^{i\phi(f',f)} \text{BW}(f')|$$

[the $f_T(1440)$ is decoupled from the $\pi\pi$ channel and therefore cannot be produced by π -exchange]. We also neglect here the $A_2(1310)$ production by B exchange since it did not improve our fits when explicitly included. The non-spin-flip wave includes all four resonances, i.e.

$$\begin{aligned} D_0^n &= 0.33 c_f \text{BW}(f) + c_A e^{i\phi(A_2,f)} \text{BW}(A_2) + c_t e^{i\phi(f_t,f)} \text{BW}(f_t) + \\ &+ 0.33 c_{f'} e^{i\phi(f',f)} \text{BW}(f'). \end{aligned}$$

The coefficients 0.33 and 0.94 were taken from a similar fit to $\pi\pi$ data, where we included only $f(1270)$. In a fit to K^+K^- data we have assumed that the OZI-forbidden production of $f'(1515)$ has the same properties. For the Breit-Wigner function (BW) we have taken the formula from Section 3 now applied to the $\bar{K}K$ decay channel. The parameters of $A_2(1310)$ were fixed at their Particle Data Group values. For $f(1270)$ we have used the values from Section 3, and for the $f'(1515)$ those from Section 5. For the relative phase between A_1 exchange (D_0^n) and π exchange (D_0^f) we have taken 270° . Leaving this parameter free did not improve our fit.

As in ref. [10] the data cannot be well described without the $f_T(1440)$, ($\chi^2/\text{DF} = 63/42$). The main discrepancy is around 1440 MeV in the t_0^4 moment. However, the p_0^4 moment is reasonably well reproduced (see fig. 3). This is due to an $A_2(1310)$ component in D_0^n . In fig. 3 we show also the p_0^0 moment which fluctuates less than the p_0^4 . We expect that this moment (not used in the fit) will also be described by the same amplitudes since

$$p_0^0 \approx \frac{m_{KK}^2}{q} \text{Im} (S^n S^{f*} + D_0^n D_0^{f*})$$

and the S-wave (not to mention other waves) is weaker than the D_0 -wave. Figure 3 shows that this is really the case.

The results of a fit with $f_T(1440)$ are shown in table 5 (values without errors have been fixed). The value χ^2/df is 36/38.

It is seen that the phases turn out to be reasonable, that of $f'(1515)$ being consistent with π exchange. Of more interest is the phase between $A_2(1310)$ produced by Z exchange [24] and $f(1270)$ produced by A_1 exchange. The value of -90° , while opposite in sign to expectation from the A_1 -Z exchange degeneracy, agrees with that found in a study of ρ - ω interference using polarized target data [25]. It is this mechanism which cancels most of the polarization effect, inclusion of $f_T(1440)$ bringing only a minor improvement in the fit to the p_0^4 moment. The parameters of $f_T(1440)$, determined mainly from the t_0^4 moment, agree quite well with those stated in Section 5 (except perhaps for the width). In particular c_t is roughly equal to $1/3$ cf as could be expected from similar couplings to $A_1\pi$ and $\bar{K}K$ channels. Actually if $c_t > 1/3 c_f$ this would mean better agreement with the width of $f_T(1440)$ as determined from the fit. The relative phase between $f_T(1440)$ and $f(1270)$ is consistent with zero as expected from the same production mechanism in a non-spin-flip component.

It might also be noted that the presence of $f_T(1440)$ influences the coupling of $f'(1515)$ to $\pi\pi$ as determined from our data. Using c_f and $c_{f'}$ from the fit, x_f from Section 3, and $\Gamma(f \rightarrow \bar{K}K)$ from Section 4, we obtain

$$\frac{f' \rightarrow \pi\pi}{f' \rightarrow \text{all}} \frac{f' \rightarrow \bar{K}K}{f' \rightarrow \text{all}} = \left(2.0 \pm 1.4 \right) \%$$

compared to $(2.2 \pm 0.7)\%$ obtained from the same data in ref. [10].

7. CONCLUDING REMARKS

We have collected the following empirical arguments in favour of $f_T(1440)$:

- i) the SU(3) and SU(6) fits to the decay widths of the $J^{PC} = 2^{++}$ nonet using in particular the value of $\Gamma(f \rightarrow \pi\pi)$ determined with high accuracy in this paper,

- ii) the discrepancy between the $f'(1515)$ parameters determined in π^- and K-induced reactions,
- iii) a coherent description of both unpolarized and polarized data at ~ 18 GeV/c.

None of these arguments is decisive. However taken together they represent reasonable evidence for a $J^{PC} = 2^{++}$ object at 1440 MeV with a width of ~ 50 MeV coupled to $\bar{K}K$ and $A_1\pi$ channels. It is the latter which might produce decisive evidence. We mean here a high statistics study of reaction

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^+ \pi^- n$$

at large energies where the phase-space maximum would be pushed far above the mass range of $f(1270)$ and $f_T(1440)$.

Even after the $f_T(1440)$ is established a question of its coupling to the $\pi\pi$ channel will remain. Having located the position of $f_T(1440)$ from reaction (2) we looked into the $\pi\pi \rightarrow \pi\pi$ data. A t_0^4 moment in our $\pi^+\pi^-$ data might have a shoulder at 1440 MeV as seen in fig. 4. However, the highest-statistics data on the reaction

$$\pi^- p \rightarrow \pi^0 \pi^0 \Delta^0$$

obtained at 8 GeV/c by the Notre Dame - Argonne Collaboration [26] exhibit a hole just in this position. Thus the decoupling of $f_T(1440)$ from the $\pi\pi$ channel can be considered as consistent with the $\pi\pi \rightarrow \pi\pi$ data.

In order to find out the sensitivity of the fit described in Section 4 to this coupling we have repeated the calculations assuming $\Gamma(f_T \rightarrow \pi\pi) = 10$ MeV, which is a maximum value allowed by our $\pi^+\pi^-$ D_0 -wave. Such a fit yields

$$\sin^2 \theta = 0.13 \begin{array}{c} + 0.04 \\ - 0.05 \end{array}$$

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Table 1
Resonance parameters determined in fits to the P_0^- and D_0 -waves

Resonance	Solution used	Mass range (MeV)	x (%)	m_R (MeV)	Γ_R (MeV)	R (GeV^{-1})	χ^2/DF
$\rho(770)$	s down	600-1380	100 (input)	777.4 ± 2.0	$160.4^{+4.1}_{-4.0}$	$5.3^{+0.9}_{-0.7}$	14.7/31
	s up			778.1 ± 2.0	$165.0^{+4.4}_{-4.1}$	$4.8^{+0.7}_{-0.6}$	18.3/31
$f(1270)$	1	1000-1560	84.9 ± 2.5	1273.3 ± 2.3	$179.2^{+6.9}_{-6.6}$	> 9.0	18.4/24
$f(1270)$	2	1000-1560	86.2 ± 1.3	1268.3 ± 2.1	$162.0^{+5.7}_{-5.5}$	> 9.6	99.8/25
Two resonances	2	1000-1560	$95.7^{+4.3}_{-6.9}$	$1280^{+5.7}_{-5.0}$	$191.9^{+10.3}_{-8.7}$	> 3.1	7.2/20
			$58.6^{+10.3}_{-27.0}$	$1467^{+18.9}_{-15.9}$	$86.1^{+34.4}_{-27.4}$		

Table 2

f-meson branching ratios

Momentum (GeV/c)	Reaction	$(f \rightarrow K\bar{K})/(f \rightarrow \pi\pi)$ (%)	Reference
1	(2)	4.7 ± 0.5	[9]
18	(2)	4.5 ± 0.9	[10]
6, 7	(3)	2.7 ± 0.9	[11]
10	(3)	3.6 ± 0.5	[12]
23	(3)	$3.7 +_{-2.0}^{0.8}$	[13]

Table 3

Results of SU(3) and SU(6) fits to $J^{PC} = 2^{++}$ meson decay widths

Type of fit	Decays fitted	Best fit	$(\chi^2/DF)_{\min}$	$(\chi^2/DF)_{\sin^2\theta=0}$
SU(3)	$f \rightarrow \pi\pi, f \rightarrow \bar{K}K$	$\sin^2 \theta = 0.18 +_{-0.05}^{+0.06}$	3.3/2	13.9/3
	$A_2 \rightarrow \bar{K}K, K^{**} \rightarrow K\pi$	$\left(0.14 +_{-0.06}^{+0.05}\right)$	(4.6/2)	(9.6/3)
SU(6)	$f \rightarrow \pi\pi, A_2 \rightarrow \rho\pi$	$\sin^2 \theta = 0.26 +_{-0.05}^{+0.06}$	2.0/2	21.9/3
	$K^{**} \rightarrow K\pi, K^{**} \rightarrow K^*\pi$	$\left(0.25 +_{-0.11}^{+0.08}\right)$	(2.0/2)	(6.2/3)
SU(3) & SU(6)	all	$\sin^2 \theta = 0.21 \pm 0.05$	4.4/3	20.4/4
		$\left(0.15 +_{-0.06}^{+0.05}\right)$	(4.5/3)	(10.3/4)

Table 4

f' resonance parameters

P_{lab} (GeV/c)	Reaction	$m(f')$ (MeV)	$\Gamma(f')$ (MeV)	Reference
13.0	(4)	1527 ± 6	61 ± 22	[18]
4.2	(5)	1522 ± 6	62^{+19}_{-14}	[19]
4.2	(4)	1520 ± 13	83 ± 23	[19]
8.25	(4),(5)	1521 ± 3	80^{+14}_{-11}	[20]
10.0	(4)	1528 ± 7	72 ± 25	[21]
18.5	(4)	1526 ± 3	79 ± 14	[22]
6.0	(2)	(1506 ± 5)	(66 ± 10)	[9]
		1496^{+9}_{-8}	69^{+22}_{-16}	[10]
7.0	(3)	1515 (fixed)	92^{+39}_{-22}	[11]
18.4	(2)	1497^{+8}_{-9}	137^{+23}_{-21}	[10]

Table 5

Results of a fit including the $f_T(1440)$ resonance

Resonances	c	m (MeV)	Γ (MeV)	Phase (°)
$f(1270)$	$7.15^{+0.86}_{-0.80}$	1273	179	0
$A_2(1310)$	$5.59^{+1.10}_{-1.15}$	1317	102	-94^{+41}_{-68}
$f_T(1440)$	$3.17^{+0.53}_{-0.60}$	1436^{+26}_{-16}	81^{+51}_{-29}	17^{+101}_{-42}
$f'(1515)$	$5.93^{+1.84}_{-2.66}$	1523	73	-161^{+18}_{-20}
$g(1700)$	$7.62^{+0.32}_{-0.34}$	1700	200	-

Figure captions

- Fig. 1 : Partial wave intensities for the reaction (1) at 17.2 GeV/c in 20 MeV bins for $0.005 < |t| < 0.200 \text{ GeV}^2/\text{c}^2$. S represents $(d^2\sigma/dt dm)|S|^2$, etc. The vertical scale is in microbarns (we do not divide by the bin size). The P_U and P_N intensities have not been plotted above 1300 MeV since they are entirely consistent with zero.
- Fig. 2 : Some results for reaction (2) at 18.4 GeV/c for $0.2 < |t| < 1.0 \text{ GeV}^2/\text{c}^2$.
a) L = 4 moments from ref. [10].
b) D-waves from ref. [4].
- Fig. 3 : t_0^4 , p_0^4 and p_0^0 moments for reaction (2) at 18.4 GeV/c for $0.01 < |t| < 0.20 \text{ GeV}^2/\text{c}^2$. The moments t_0^4 and p_0^4 have been fitted by the formulae described in the text. The solid line shows the best fit with the $f_T(1440)$, the dashed one that without the $f_T(1440)$. The fit results are also shown for the p_0^0 assuming that other waves (mainly the S-wave) are much weaker than the D_0 -wave.
- Fig. 4 : t_0^4 moment for the $\pi\pi \rightarrow \pi\pi$ data. Open circles represent our data at 17.2 GeV/c; the black dots denote the 8 GeV/c $\pi^0\pi^0$ data of the Notre Dame - Argonne Collaboration [24]. The vertical scale is in arbitrary units.

Fig. 1

Fig. 2

Fig. 3

Fig. 4