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Is the $f_1(1420)$ Our First Hybrid Meson?

Shin ISHIDA, Masuho ODA,* Haruhiko SAWAZAKI
and Kenji YAMADA*)

*Atomic Energy Research Institute, College of Science and Technology
Nihon University, Tokyo 101*
**Faculty of Engineering, Kokushikan University, Tokyo 154*

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It is argued that the f_1 (1420) is probably a ground-state hybrid meson, $(u\bar{u}+d\bar{d})g/\sqrt{2}$. The decay properties of the other members of ground-state hybrid-meson nonets with $J^{PC}=1^{+-}$ and $(0, 1, 2)^{++}$ are studied in the framework of an extended covariant oscillator model. On this basis several plausible corresponding candidates are assigned.

§ 1. Introduction

Recently it has become evident[1)] that there exist several meson resonances in the mass region of $1\sim2$ GeV which are difficult to be classified as ordinary $q\bar{q}$ states. These special mesons are possible candidates for glueballs or hybrid $q\bar{q}g$ states or four-quark $qq\bar{q}\bar{q}$ states, whose existence is expected from quantum chromodynamics (QCD). Concerning the positive parity mesons[2)] which have been observed in the mass region of $1.0\sim1.6$ GeV, most of them are definitely classified[1),3)] as members of the P-wave $q\bar{q}$-meson nonets: The $^3P_2$ tensor nonet has been established, while the $^3P_0$ scalar nonet is too controversial to give any definite statement. The assignments to the $^3P_1$ and $^1P_1$ nonets ($J^{PC}=1^{++}$ and 1^{+-}, respectively) have been almost fixed except for the respective remaining isoscalar partners (with mainly $s\bar{s}$ component) of $f_1(1285)$ and $h_1(1170)$ (with mainly $n\bar{n}$ component, n denoting u or d quark). In this situation we are especially interested in the isoscalar $J^{PC}=1^{++}$ mesons. Now it has been confirmed the existence of three resonances with these quantum numbers, $f_1(1285)$, $f_1(1420)$ and $f_1(1530)$. In our previous work[3)] we have already pointed out that the recently confirmed resonance[4),5)] $f_1(1530)$ may be more plausible as the above-mentioned partner of $f_1(1285)$ than the usually supposed partner $f_1(1420)$. In this article we suppose further that the $f_1(1420)$ may be a hybrid $q\bar{q}g$ meson with mainly $n\bar{n}$-quark component.

§ 2. Key experimental facts and our reasoning for the $f_1(1420)$ as a hybrid meson

The $f_1(1420)$ has[2)] a mass and width of 1422 ± 10 MeV and 55 ± 3 MeV, respectively, and decays predominantly, through an intermediate state K^*K, to $K\bar{K}\pi$. In the following we give our reasoning and collect important experimental facts, which have led us to the choice of $f_1(1530)$ instead of $f_1(1420)$ as the partner of $f_1(1285)$ and suggested the $f_1(1420)$ being a hybrid meson "$f_{g1}(1420)$".

(*a*) $J^{PC}=1^{++}$ *property of* $f_1(1420)$

*) Present address: Physical Science Laboratory, College of Science and Technology, Nihon University, Funabashi, Chiba 274.

A K^*K resonance, $X(1420)$, at $M\approx1420$ MeV with $\Gamma\approx40$ MeV has been observed[6)~9)] in the reaction $\gamma\gamma^*\to K^{\pm}K_S{}^0\pi^{\mp}$, where γ^* denotes an off-mass-shell photon, while no resonance has been seen near 1420 MeV in the reactions of two real photons. This behavior indicates that the $X(1420)$ has spin 1, since two real photons are forbidden by the Landau-Yang theorem[10)] to couple to a spin-1 state. The analyses of decay angular distributions show[8)] that the $J^{PC}=1^{++}$ assignment is favored, although negative parity*) cannot be excluded. Since the mass, width and decay properties of $X(1420)$ are all consistent with those of the $f_1(1420)$ observed[12)~14)] in hadronic collisions, we identify the $X(1420)$ with the $f_1(1420)$.

(*b*) *Gluon-rich character of* $f_1(1420)$

The $f_1(1420)$ has been observed in two different types of hadroproduction experiment: One is the central production[12)] in the reactions $(\pi^+/p)p\to(\pi^+/p)(K^{\pm}K_S{}^0\pi^{\mp})p$ and the other is the peripheral production[13),14)] in the reactions $\pi^-p\to(K^{\pm}K_S{}^0\pi^{\mp})n$. However the $f_1(1420)$ is produced much more preferentially in the former reaction than in the latter.[12),14),15)] This suggests that the $f_1(1420)$ may contain a constituent gluon, since the former production mechanism is presumably dominated by double pomeron or pomeron-Reggeon exchange and the pomeron exchange is interpreted as multigluon exchange[16)] in QCD.

(*c*) $n\bar{n}$*-quark component mainly contained in the* $f_1(1420)$

In the decays $J/\psi\to\omega K^{\pm}K_S{}^0\pi^{\mp}$ and $\omega K^+K^-\pi^0$ a clear peak with $M=1442\pm5^{+10}_{-17}$ MeV and $\Gamma=40^{+17}_{-13}\pm5$ MeV has been observed[17)] in the $K\bar{K}\pi$ system (through a K^*K intermediate state) recoiling against ω. The decay angular distributions do not favor a $J^P=0^-$ assignment but are consistent with $J^P=1^+$. No corresponding signal has been seen[17),18)] in the decays $J/\psi\to\phi K^{\pm}K_S{}^0\pi^{\mp}$ and $\phi K^+K^-\pi^0$. Comparing the values of mass and width, it is reasonable to identify this resonance with the $f_1(1420)$ observed in the hadronic collisions. The fact that this $f_1(1420)$ is produced accompanied by ω and not by ϕ implies, due to the OZI rule, that it has a considerable amount of $n\bar{n}$-quark component and no substantial $s\bar{s}$ component.

(*d*) $f_1(1530)$ *a likelier member of the* $^3P_1$ $q\bar{q}$ *nonet?*

The investigation of K^*K resonances has also been made in another type of experiment, the strangeness-exchanging peripheral reactions, $K^-p\to(K^{\pm}K_S{}^0\pi^{\mp})\Lambda$. In this experiment, while no clear peak[5)] of the $f_1(1420)$ has been observed, instead a $J^{PC}=1^{++}$ resonance $f_1(1530)$ with $M=1530\pm10$ MeV and $\Gamma=100\pm40$ MeV has been observed.[5),4)] In this reaction, assuming the OZI rule, both of simple $q\bar{q}$ mesons with $s\bar{s}$ component and ones with $u\bar{u}$ component are expected to be equally well produced, if the contribution of light meson poles (of K and K^*) dominates the strangeness-exchanging peripheral process. Hence the above experimental fact of no observation of the $f_1(1420)$ seems to be natural from its gluon-rich character mentioned in (*b*), and the fact of clear observation of the $f_1(1530)$ seems, considering also the fact of its

*) Actually it has been suggested that the $X(1420)$ might be a hybrid $q\bar{q}g$ state with an exotic quantum number $J^{PC}=1^{-+}$; see Ref. 11).

comparatively less production[14] in the $\pi^- p$ peripheral process, to strongly suggest that the $f_1(1530)$ may be the remaining isoscalar member (with mainly $s\bar{s}$ component) of the $^3P_1\ q\bar{q}$ nonet.

(*e*) *Analysis of* $f_1 \to \phi\gamma$ *in favor of* $f_1(1530)$ *over* $f_1(1420)$ *as the* $s\bar{s}$ *member*

Recently the radiative decay of isoscalar 1^{++} mesons into $\phi\gamma$ has been investigated[19] by the peripheral reaction $\pi^- p \to (K^+K^-\gamma)n$ and the $\phi\gamma$ decay of $f_1(1285)$ has been observed, while those of $f_1(1420)$ and $f_1(1530)$ not observed. The experimental upper limits for the ratios of the numbers of these missing events to that of the $f_1(1285)$ were given,[19),20)] respectively, as $R[f_1(1420)]<0.6$ and $R'[f_1(1530)]<1.1$.*) If the $f_1(1285)$ and the $f_1(1420)$ [$f_1(1530)$] are isoscalar partners of the same nonet, the ratio $R[R']$ can be expressed,[19] considering this peripheral process is dominated by a simple meson pole (assuming the OZI rule and the $\phi(1020)$ to be a pure $s\bar{s}$ state), as

$$R=\frac{\Gamma[f_1(1285)]}{\Gamma[f_1(1420)]}\cdot\frac{\Gamma^{\gamma}[f_1(s\bar{s};1420)]}{\Gamma^{\gamma}[f_1(s\bar{s};1285)]}, \quad R'=R[f_1(1420)\to f_1(1530)],$$

where the Γ's are the total widths of corresponding mesons and the Γ^{γ}'s are the "characteristic" partial decay widths into $\phi\gamma$ of the respective "ideal" f_1 mesons assumed to be pure $s\bar{s}$ states. These expressions are very useful since they are independent of the mixing angles between the partners. Taking[2] $\Gamma[f_1(1285)]=25$ MeV, $\Gamma[f_1(1420)]=55$ MeV and $\Gamma[f_1(1530)]=106$ MeV and using our theoretical values,[3] based on the covariant oscillator quark model, of the respective characteristic radiative widths Γ^{γ}, we estimate**) $R\approx0.64$ and $R'\approx0.41$. The latter value of R' for the $f_1(1530)$ is quite compatible with the experimental limit given above, while the former value of R for the $f_1(1420)$ seems not to be favored by the corresponding limit. Hence the $f_1(1530)$ seems***) to be a more plausible partner (with mainly $s\bar{s}$ component) of the $f_1(1285)$.

(*f*) $f_1(1420)$ *not expected to be a four-quark*****) *or glueball state*

We naively expect that, in the mass region of $1.4\sim1.5$ GeV, four-quark states with negative parity (corresponding to the first-excited states) rather than the positive-parity ones may exist, since we have two good candidates[22] for them in this mass region, i.e., a 1^{--} $\phi\pi$ resonance[23] $\rho(1480)$ with $M=1480\pm40$ MeV and $\Gamma=130\pm60$ MeV and an exotic 1^{-+} $\eta\pi$ resonance[24] $M(1405)$ with $M=1406\pm20$ MeV and $\Gamma=180\pm30$ MeV. Concerning the possibility of the $f_1(1420)$ being a glueball state, we merely refer to the fact that in any models the 1^{++} glueball is not expected[25] to lie in such a low-mass region as 1.42 GeV.

Thus putting all the above arguments $(a)\sim(f)$ together, it seems that the $f_1(1420)$

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*) This limit is given for a resonance with $M\approx1.5\sim1.6$ GeV and $\Gamma\gtrsim150$ MeV.

**) The estimate by a nonrelativistic quark model, where $\Gamma^{\gamma}\propto q^3$ (q being photon momentum), gives $R\approx R'\approx1.4$, as in Ref. 19). However, this q-dependence of Γ^{γ} may not be correct; see Ref. 3).

***) Our general analysis of the meson radiative decay gives the mixing angle, the value of $\approx16°\sim29°$ in the ideal basis, between the $f_1(1285)$ and the $f_1(1530)$, which is in agreement with the value of $\approx21°$ obtained from the quadratic mass formula; see Ref. 3).

****) However, as for the opposite viewpoint, see Ref. 21).

is most probably a hybrid $(u\bar{u}+d\bar{d})g/\sqrt{2}$ meson.

§ 3. Our model scheme for hybrid mesons and its ground-state spectrum

We shall regard[26)~28)] hybrid $q\bar{q}g$ mesons as color singlet bound states, confined by a harmonic potential, of a quark, an antiquark and a gluon with respective "constituent" masses, and treat them in the framework of an "extended" covariant oscillator quark model. The idea that the gluon has an effective mass dynamically generated at large distances has been advocated[29)] in continuum QCD and recently this has been actually demonstrated[30)] in numerical studies of the gluon propagator in Landau gauge in lattice QCD. This idea has also been supported by a phenomenological point of view.[31)] The effective mass value is in the range of about $500\sim800$ MeV according to these analyses.

The extension of the covariant oscillator quark model[32)] is made so as to be applicable to the systems containing massive vector constituents. The hybrid mesons of quark-antiquark-gluon systems are described as a trilocal field (wave function) $\Phi^{\beta}_{\alpha\mu}(x_1, x_2, x_3)$, where x_1, x_2 and x_3 are the space-time coordinates of a constituent quark, antiquark and gluon, respectively, $\alpha(\beta)$ $(\alpha, \beta=1\sim4)$ represents the Dirac-spinor index of a quark (antiquark), μ $(\mu=1\sim4)$ the spin index of a vector gluon, and the flavor and color indices are omitted for simplicity. The spin and the space-time part of the wave function are covariantly extended, separately, from the corresponding parts of the nonrelativistic one. The spin wave function $\Phi^{\beta}_{\alpha\mu}$ satisfies the Bargmann-Wigner equation[33)] concerning the quark (antiquark) spin $\alpha(\beta)$ and Lorentz condition, $P_\mu\Phi^{\beta}_{\alpha\mu}=0$ (P_μ being the total four-momentum of systems). The space-time wave function is determined by a Klein-Gordon-type equation with a squared-mass operator of the form of four-dimensional harmonic oscillator, where the confining potential is assumed[26)~28)] to be an additive two-body interaction and its strength to be simply proportional to $\sum_a T_a^{(i)} T_a^{(j)}$ (T_a being the color $SU(3)$ generators and the superscripts labeling the interacting constituents). Here it should be noted that we choose the definite-metric-type normalizable wave function,[34)] which gives the desirable asymptotic behavior for the electromagnetic form factors of ordinary hadrons and the moderate form factor effect[3)] in the radiative decays of P-wave $q\bar{q}$ mesons. (This type of wave function seems to play also desirable roles in this analysis of the decay of hybrid mesons, see the later part.)

In the present model hybrid $q\bar{q}g$ states are classified similarly as in the corresponding nonrelativistic models. The ground states are constructed from a relative S-wave quark-antiquark pair in a color octet with $J^{PC}=0^{-+}$ or 1^{--} and a massive gluon with 1^{--} mutually in the S-wave state. Thus we have four $q\bar{q}g$ flavor nonets with $J^{PC}=1^{+-}$, $(0,1,2)^{++}$. (We only consider hybrid mesons composed of u, d and s quarks.) It is notable that in our model the lowest-lying states have positive parity. This is in strong contrast to the bag model,[35),36)] where these states have negative parity and are expected to lie in the $1\sim2$ GeV mass range.

We most naively estimate the masses of ground-state hybrid mesons, assuming that they are given by the simple sum of the constituent masses. If we take half of

ρ- and ϕ-meson mass for the u, d-quark and s-quark mass, respectively, and 500 ~ 800 MeV for the gluon mass, we find the mass of $n\bar{n}g$, $n\bar{s}g$ or $s\bar{n}g$, and $s\bar{s}g$ states to be 1270 ~ 1570 MeV, 1390 ~ 1690 MeV and 1520 ~ 1820 MeV, respectively. It is interesting that the mass of $f_1(1420)$ is within the range of 1270 ~ 1570 MeV estimated in this way.

§ 4. Decay properties of the hybrid mesons

Now we investigate the decays of hybrid $q\bar{q}g$ mesons into two ordinary mesons, $H \to M_A + M_B$, in our model scheme. We assume[26),36),37)] that these decays proceed by the conversion of the gluon into a $q\bar{q}$ pair as shown in Fig. 1. Then the invariant effective action for all the relevant interactions is, in a unified manner, given as the following overlap integral:

$$I_{\rm int} = \int d^4x_1 d^4x_2 d^4x_3 [\bar{\Phi}^{(B)}{}_\beta{}^\delta(x_3, x_2) \times (\Gamma_{3\mu})_\delta{}^\gamma \bar{\Phi}^{(A)}{}_\gamma{}^\alpha(x_1, x_3) \Phi^{(H)\beta}{}_{\alpha\mu}(x_1, x_2, x_3) + \text{H.C.}],$$

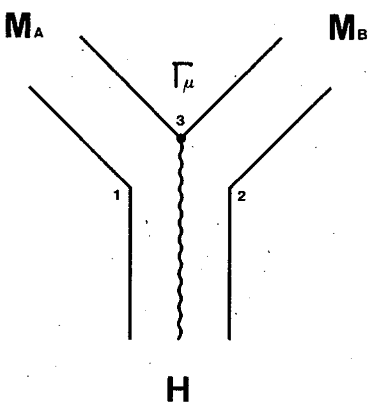

Fig. 1. Decay mechanism of hybrid mesons into two ordinary mesons.

where $\Phi^{(A)}{}_\gamma{}^\alpha(x_1, x_3)$, etc. are bilocal fields (wave functions) describing all the states in the final $q\bar{q}$ mesons and Γ_μ is a quark-gluon vertex operator given as the sum of two terms[38)] corresponding to the color "electric" current and the color "magnetic" current, respectively. Thus we can express the decay widths for all relevant possible channels in terms of

Table I. Characteristic decay properties of the ground-state hybrid mesons.

J^{PC}	Hybrid meson[a)]	Characteristic width	Main decay mode[b)]	J^{PC}	Hybrid meson[a)]	Characteristic width	Main decay mode[b)]
0^{++}	a_{g0}(1200 ~ 1400)	Narrow	$\eta\pi$	2^{++}	a_{g2}(1400 ~ 1600)	Narrow	$\rho\pi$
	K^*_{g0}(1300 ~ 1500)	Narrow	$K\pi$		K^*_{g2}(1500 ~ 1700)	Narrow	$K^*\pi$
							$(K^*\rho)$[c)]
	f_{g0}(1200 ~ 1400)	Ordinary	$\pi\pi$		f_{g2}(1400 ~ 1600)	Narrow	$\pi\pi$
							$(\rho\rho)$[c)]
	f'_{g0}(1450 ~ 1650)	Narrow	$K\bar{K}$		f'_{g2}(1650 ~ 1850)	Narrow	$K^*\bar{K}$
							$(K^*\bar{K}^*)$[c)]
1^{++}	a_{g1}(1300 ~ 1500)	Broad	$\rho\pi$	1^{+-}	b_{g1}(1300 ~ 1500)	Narrow	$\omega\pi$
	$K^{(A)}_{g1}$(1400 ~ 1600)	Broad	$K^*\pi$		$K^{(B)}_{g1}$(1400 ~ 1600)	Narrow	$K^*\pi$
	f_{g1}(1420)	55 MeV (input)	$K^*\bar{K}$		h_{g1}(1300 ~ 1500)	Narrow	$\rho\pi$
	f'_{g1}(1550 ~ 1750)	Broad	$K^*\bar{K}$		h'_{g1}(1550 ~ 1750)	Narrow	$K^*\bar{K}$

a) Our symbols for hybrid mesons conform to the standard naming scheme for $q\bar{q}$ mesons except for the subscript g indicating extra gluon. As for the isoscalar states we take the "ideal" configuration, $(f_g, h_g) = (u\bar{u} + d\bar{d})g/\sqrt{2}$ and $(f_g', h_g') = s\bar{s}g$.

b) The singlet-octet mixing angle for η and η' is taken to be $-20°$.

c) If the mass of the initial hybrid meson is large enough, this becomes a main decay mode.

the two coupling parameters (corresponding to the above two types of gluonic currents). Actually we estimate only the decay widths of the ground-state hybrid-meson nonets into two S-wave ground-state mesons: We would expect that these decay channels almost saturate the decay of the hybrid meson, since contributions from such decay channels as an S-wave plus P-wave $q\bar{q}$ meson and a hybrid (or glueball) plus $q\bar{q}$ meson, and from the direct multibody decays will be small (or kinematically forbidden) because of the low mass of initial hybrid mesons. We use the experimental width $\Gamma[f_1(1420)\to K^*K]\approx 55$ MeV as input to fix the absolute scale of coupling strength. (As for a parameter value of the magnetic coupling we use the same one obtained from the analysis[38] of the spin-spin splitting of $q\bar{q}$ mesons.) We give the result in Table I, where are shown only the two characteristic decay features of the respective hybrid mesons: their expected main decay modes and total decay widths, classified into three groups, *"Narrow"* group with $\Gamma \lesssim 100$ MeV, *"Ordinary"* group with $100\text{ MeV} \lesssim \Gamma \lesssim 250$ MeV and *"Broad"* group with $\Gamma \gtrsim 250$ MeV. In the present stage of almost no available information on hybrid mesons (even on their mass values) we should be satisfied with discussing such qualitative features.

§ 5. Other possible candidates for the hybrid mesons

Now by making use of our predicted decay properties of the ground-state hybrid mesons collected in Table I, we select several possible candidates [other than the

Table II. Experimental candidates for the ground-state hybrid mesons. Their expected branching ratios for main decay modes are also given.

Meson Mass (MeV)	Width (MeV)	Observed channels	[Ref.]	Possible assignment	Expected branching ratio[a)]
$a_0(1300)$ 1300 ± 31	130 ± 29	$\eta\pi$	[39]	a_{g0}	$\eta\pi$ $K\bar{K}$ $\eta'\pi$ 1 : 0.59 : 0.25
$f_0(1240)$ 1240 ± 22	140 ± 22	$K\bar{K}$	[2]	f_{g0}	$\pi\pi$ $K\bar{K}$ $\eta\eta$ 1 : 0.20 : 0.07
$f_0(1525)$ ≈1525	≈90	$K\bar{K}$	[2]	f'_{g0}	$K\bar{K}$ $\eta\eta$ $\eta\eta'$ 1 : 0.10 : 0.09
$f_2(1430)$ ≈1430	$\approx10\sim100$	$\pi\pi$, $K\bar{K}$	[2]	f_{g2}[b)]	$\pi\pi$ $K\bar{K}$ $\eta\eta$ 1 : 0.07 : 0.02
$f_2(1640)$ 1643 ± 7	<70	$\omega\omega$	[40]	f_{g2}[b)]	$\rho\rho$ $\omega\omega$ 1 : 0.29 $\pi\pi$ $K\bar{K}$ $\eta\eta$ 1 : 0.11 : 0.04
$b_1(1310)$ 1311 ± 10	126 ± 10	$\eta(\pi\pi)_\rho$	[41]	b_{g1}	$\omega\pi$ $\rho\eta$ 1 : 0.3[c)]
$K_1(1650)$ 1650 ± 50	150 ± 50	ϕK	[2]	$K_{g1}^{(B)}$[d)]	$K^*\pi$ ρK ϕK ωK 1 : 0.91 : 0.36 : 0.30

a) See footnote b) of Table I.
b) Either the $f_2(1430)$ or the $f_2(1640)$ would be mainly f_{g2} of $(u\bar{u}+d\bar{d})g/\sqrt{2}$, and the rest might be a glueball or something rather than mainly f'_{g2} of $s\bar{s}g$.
c) This value is obtained by simply taking the mass of ρ meson to be ≈ 700 MeV (note that the mass of $b_1(1310)$ is just below the $\rho\eta$ threshold at 1320 MeV and decays to $\rho\eta$ only virtually).
d) The $K_1(1650)$ would be a mixed state of $K_{g1}^{(A)}$ and $K_{g1}^{(B)}$.

$f_1(1420)$] for them out of observed mesons still unclassified. They are collected in Table II, where the experimental masses, total decay widths and observed channels of the respective candidates are shown. Our primary reason for selecting the scalar mesons $a_0(1300)$, $f_0(1240)$ and $f_0(1525)$ is that they have comparatively narrow widths, since they would be, in the case of $q\bar{q}$ states, expected to be very broad in most of the quark-model calculations. The candidates $b_1(1310)$, $f_2(1430)$ and $f_2(1640)$, if they really exist, will certainly be non-$q\bar{q}$ states, since there are no places for them in the corresponding $q\bar{q}$ nonets.

Comparing the experimental decay widths of the candidates in Table II with our theoretical characteristic widths, we find that they are almost in agreement except for the $b_1(1310)$. Here it is worth noting that the candidates belonging to the broad group may have too large widths to be easily observed. In Table II we have also given the expected branching ratios for main decay modes of the respective candidates which are calculated, independent of the details of our model, only from the flavor symmetry with the OZI rule and phase space correction assuming the lowest possible partial-wave decays. It is quite interesting that the three candidates $a_0(1300)$, $f_0(1525)$ and $f_2(1430)$ out of the seven have been observed through the channels with the largest branching ratio and the others through the channels with the second largest or the comparatively large ratio. In this connection it is of critical importance for the present model to check experimentally the existence of those candidates in the following respective channels; $f_0(1240)$ in $\pi\pi$, $f_2(1640)$ in $\rho\rho$, $b_1(1310)$ in $\omega\pi$ and $K_1(1650)$ in $K^*\pi$ and ρK.

The results of more detailed and extensive analyses for the hybrid meson decays will be published elsewhere.

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Nate added in proof: The properties of the $f_1(1420)$ of $J^{PC}=1^{++}$ and decaying predominantly to K^*K have been further confirmed by the recent experiments [WA 76 Collaboration, T. A. Armstrong et al., Phys. Lett. **B221** (1989), 216; Z. Phys. **C43** (1989), 55].