



The Thomas Jefferson National Accelerator Facility  
Theory Group Preprint Series

hep-ph/9709231  
JLAB-THY-97-37

## Implications of a $J^{PC}$ exotic

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September 1997

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The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

### Abstract

Recent experimental data from BNL on the isovector  $J^{PC} = 1^{-+}$  exotic at 1.6 GeV indicate the existence of a non-quarkonium state consistent with lattice gauge theory predictions. We discuss how further experiments can strengthen this conclusion. We show that the  $\rho\pi$ ,  $\eta'\pi$  and  $\eta\pi$  couplings of this state qualitatively support the hypothesis that it is a hybrid meson, although other interpretations cannot be eliminated.

There are two independent indications of an isovector  $J^{PC} = 1^{-+}$  exotic resonance  $\tilde{\rho}(1600)$  in  $\pi^-N \rightarrow \pi^+\pi^-\pi^-N$ . The E852 collaboration at BNL recently reported evidence for a resonance at  $1593 \pm 8$  MeV with a width of  $168 \pm 20$  MeV [1]. These parameters are consistent with the preliminary claim by the VES collaboration of a resonance at  $1.62 \pm 0.02$  GeV with a width of  $0.24 \pm 0.05$  GeV [2]. In both cases a partial wave analysis was performed, and the decay mode  $\rho^0\pi^-$  was observed.

In this letter we indicate that experimental and lattice gauge theory  $1^{-+}$  mass estimates are converging. To further verify the experimental signal and to provide independent confirmation, we suggest a search in other decay channels and for other  $J^{PC}$  exotic resonances.

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If current experimental data are taken at face value, we show that the  $\rho\pi$ ,  $\eta'\pi$  and  $\eta\pi$  couplings of  $\hat{\rho}(1600)$  qualitatively supports the hypothesis that it is a hybrid meson, although other interpretations cannot be eliminated. We indicate further production mechanisms.

There are several reasons to believe that the resonance at 1.6 GeV is not an experimental artifact:

1. Although the  $1^{-+}$  signal is weak, the well-known states  $\pi(1300)$  and  $\pi(1800)$  are of similar intensity and are clearly seen, suggesting that the exotic signal should be taken seriously [1, 2].
2. An extensive study was done by E852 to eliminate any sources of spurious signals. Instrumental acceptance and smearing of angular distributions (called “leakage”) have been analysed, but the  $J^{PC} = 1^{-+}$  peak at 1.6 GeV appears to be robust. The fact that  $\hat{\rho}(1600)$  survives the leakage studies is non-trivial, given that the exotic signal below 1.5 GeV was shown to be an artifact of leakage. There is *a priori* the possibility that the only known state with a mass in the range 1.5 – 1.7 GeV which can contribute (within isospin symmetry) in the  $\pi^+\pi^-\pi^-$  channel, the  $\pi_2(1670)$ , can appear as a  $1^{-+}$  signal due to leakage. E852 finds the  $\pi_2(1670)$  mass to be  $1683 \pm 4$  MeV [3], which is not only very precise but also consistent with the PDG value  $1670 \pm 20$  MeV [4]. The width measured by E852 is  $277 \pm 10$  MeV, consistent with the PDG value  $258 \pm 18$  MeV. These masses and widths are very different from those measured for the exotic signal.
3. E852 observes rapid phase motion in the 1.5–1.7 GeV region relative to the  $0^{-+}$ ,  $2^{++}$ ,  $1^{++}$  and  $2^{-+}$  partial waves. It is impressive that clear phase motion is observed relative to the nearby  $\pi_2(1670)$ . VES preliminarily indicated proper phase variation with respect to the  $2^{++}$  wave, although the details of the phase motion is somewhat different [2]. The overall conclusion is that  $\hat{\rho}(1600)$  is resonant.
4. The preliminary E852 analysis of  $\pi^-N \rightarrow \pi^-\pi^0\pi^0N$  is consistent with most of the features in the  $\pi^-N \rightarrow \pi^+\pi^-\pi^-N$  analysis [5].

E852 showed that the  $\hat{\rho}(1600)$  is produced slightly more strongly in cases where the incoming pion beam couples to the exchanged  $b_1$  or  $f_1$  Regge trajectories, rather than the  $\rho$  or  $f_2$  trajectories [1]. This suggests that exchange of states more massive than 1 GeV can be important for production of  $\hat{\rho}(1600)$ .

Further indications that there may be an exotic at 1.6 GeV are:

1. VES reported a broad structure peaking at  $\sim 1.6$  GeV (recently estimated to be  $1595 \pm 17 \pm 10$  MeV [6]) with considerably stronger coupling to  $\eta'\pi$  than  $\eta\pi$  for invariant masses greater than 1.4 GeV when the effects of phase space have been removed [2]. There is no phase motion against the  $a_2$ , indicating that it is non-resonant.
2. BNL and VES reported a  $1^{-+}$  exotic wave in  $f_1\pi$ , which is unlikely to arise from misidentification of the dominant  $1^{++}$  structure due to the similar intensity of the  $1^{-+}$  and  $1^{++}$  waves [7, 8, 9]. However, it is experimentally challenging to reconstruct the  $f_1$  and the results should hence be regarded with some caution as “more data would be required for a firm conclusion” [7]. Particularly, we note that  $\sim 500$  events per 100 MeV bin were collected by BNL and VES in the  $f_1\pi$  channel [7, 9], compared with  $\sim 10000$  events per 100 MeV bin in  $\rho\pi$  [1]. The  $K^+\bar{K}^0\pi^-\pi^-$  channel analysed by BNL yielded a structure at 1.7 GeV which decayed to  $f_1\pi$ . However, they report no phase motion relative to the dominant  $1^{++}$  structure, indicating that it is non-resonant if the  $1^{++}$  is non-resonant. This is confirmed by recent data from BNL which shows  $1^{-+}$  peaking at 1.7 – 1.8 GeV in  $f_1\pi \rightarrow \eta\pi^+\pi^-\pi^-$  [8], while VES finds a peak at 1.7 – 1.8 GeV in the same channel [9].

A second, independent, reason to support an exotic signal at greater than 1.5 GeV arises from narrowing estimates for  $1^{-+}$  masses from lattice gauge theory. There are two groups that have predicted  $s\bar{s}$   $1^{-+}$ , the UKQCD [10] and MILC collaborations [11, 12]. These groups have considerable facility to separate the lightest  $1^{-+}$  state for a given quark mass. MILC has presented evidence that operators, whether they are hybrid-like or four-quark like, easily select the lowest-lying state, indicating a strong coupling of either operator to the  $1^{-+}$  state. It is important to emphasize that quenched lattice calculations allow Fock state components with  $Q\bar{Q}$  and  $Q\bar{Q}Q\bar{Q}$  quark structure, and that the quark Fock state decomposition of the lowest-lying  $1^{-+}$  is by no means determined by these calculations. Although lattice calculations in the quenched approximation contain systematic errors due to contamination from higher excited states and lattice artifacts, they are settling down on an  $s\bar{s}$  mass estimate. UKQCD estimates  $1990 \pm 130$  MeV, where the error is statistical. MILC quotes  $2170 \pm 80$  MeV with an additional  $\sim 200$  MeV systematic error. Systematic errors do not include errors due to the quenched approximation. Taking the mass difference between light and  $s\bar{s}$  hybrids to be similar to conventional mesons, we expect light quark hybrids to be  $\sim 200 - 250$  MeV lighter [4], i.e.  $(1.75 - 2) \pm 0.2$  GeV. In fact, MILC finds

1970  $\pm$  90 MeV from an extrapolation of hybrid masses to light quarks, with a systematic error of 300 MeV.

The existence of  $\hat{\rho}(1600)$  may be confirmed by searching for its presence in hitherto unexplored decay channels like  $K^*K$ , but particularly<sup>1</sup> in  $b_1\pi$ . A  $b_1\pi$  analysis is in progress at BNL and has provisionally been approved at TJNAF [13].

Another way to confirm the isovector  $1^{-+}$  at 1.6 GeV is by searching for its non- $s\bar{s}$  isoscalar partner in the same mass region. Decays to the final states  $\eta'\eta$ ,  $\rho\rho$  and  $\omega\omega$  are expected<sup>2</sup>, although the first mode is suppressed by symmetrization selection rules [14, 15]. Null results in  $\eta'\eta$  should confirm the selection rule.  $K^*K$  and  $a_2\pi$  are also search channels, and a study of  $K^*K$  is already under way at BNL, although nothing has been reported in this channel by VES [9]. Additional channels<sup>3</sup> are  $\pi(1300)\pi$  and  $a_1\pi$ , but these involve broad final states. From the decay modes listed it follows that production via incoming pions<sup>4</sup> at BNL and VES can only proceed via exchange of states more massive than 1 GeV. Photoproduction at TJNAF can occur via  $\rho$  exchange.

The existence of  $\hat{\rho}(1600)$  can be confirmed by searching for the  $J^{PC}$  exotic partners  $0^{+-}$ ,  $2^{+-}$  and  $0^{--}$ . Lattice gauge theory estimates for their  $s\bar{s}$  masses exist. UKQCD estimates that the  $0^{+-}$  and  $2^{+-}$  are respectively  $0.2 \pm 0.2$  GeV and  $0.7 \pm 0.3$  GeV more massive than the  $1^{-+}$  [10]. MILC remarks that  $0^{+-}$  is “clearly heavier than the  $1^{-+}$ ” and estimates the mass difference to be  $0.2 \pm 0.1$  GeV (for  $c\bar{c}$ ) [12]. The message appears to be that the  $0^{+-}$  is only slightly heavier than the  $1^{-+}$ . No firm numerical estimate exists for the  $0^{--}$  exotic, suggesting that if it exists at all, it is very heavy [12].

The isovector  $0^{+-}$  can decay to  $\pi\pi$  and  $\rho\rho$ , but these decays are suppressed by symmetrization selection rules [15].  $b_1\eta$  and  $K_1(1270)K$  are possible, but may be suppressed by P-wave phase space. Decays to  $a_1\pi$ ,  $h_1\pi$  and  $\pi(1300)\pi$  involve broad final states<sup>5</sup>. The isovector  $0^{+-}$  may hence be very challenging to isolate experimentally due to its lack of coupling to tractable final states [16].

<sup>1</sup> $b_1\pi$  is the dominant mode predicted in flux-tube models [16].

<sup>2</sup> $0^{+-}$ ,  $1^{-+}$  and  $2^{+-} \rightarrow \pi^0\pi^0, \pi^+\pi^-, K^+K^-, K^0\bar{K}^0, \eta\eta$  and  $\eta'\eta'$  are forbidden by CP conservation and Bose symmetry.

<sup>3</sup>Dominant channels for flux-tube model hybrids [16].

<sup>4</sup>Throughout this work we shall assume that s-channel and u-channel production of states in the mass range of interest are suppressed, since very heavy  $\approx 3$  GeV excited nucleons would have to be produced for this mechanism to be viable.

<sup>5</sup>Dominant channels for flux-tube model hybrids [16].

The isoscalar  $0^{+-}$  can decay to  $K_1(1270)K$  and  $h_1\eta$ , but both are likely to be suppressed by P-wave phase space. The *only* other strong decay mode that is expected to be significant is  $b_1\pi$ . This leads to the extraordinary prediction that the isoscalar  $0^{+-}$  essentially only couples to  $b_1\pi$ . This mode should be allowed in future  $b_1\pi$  analyses.

For both the isovector and isoscalar  $0^{+-}$  an incoming pion beam at VES and BNL can couple only to exchanged mesons more massive than 1 GeV. In the case of the isoscalar this is also true for a photon beam at TJNAF. However, the isovector can be photoproduced via  $\rho$  exchange.

Lastly we consider the  $2^{+-}$  states. These are expected to be more massive than the  $1^{-+}$  and  $0^{+-}$  exotics, and have more decay channels than the  $0^{+-}$  states even at the same mass. We hence *a priori* expect these states to be wider<sup>6</sup>. This disadvantage is partially offset by the fact that these states can decay to final states which are easy to access experimentally, some of which we list here. Particularly, the isovector can decay to  $\omega\pi$ ,  $K^*K$ ,  $\rho\eta$  and  $\rho\rho$ . Note that decay to  $\pi\pi$  is suppressed by symmetrization selection rules [15]. The isoscalar couples to  $\rho\pi$ ,  $K^*K$  and  $\omega\eta$ . The allowed decays listed are suppressed D-wave phase space. The  $2^{+-}$  states can be produced at VES and BNL via vector meson exchange and at TJNAF via  $\pi$  and  $\eta$  exchange (and  $\rho$  exchange for the isovector). Additional modes to narrow final states are  $K_1(1270)K$ , as well as isovector  $2^{+-}$  decay to  $a_2\pi$  and isoscalar decay to  $b_1\pi$ .

We proceed to estimate the  $\rho\pi$  coupling of  $\hat{\rho}(1600)$ . Estimates for  $\rho\pi$  couplings can be obtained by noticing that the E852 pion beam experiment established that  $a_2$ ,  $a_1$  and  $\pi_2(1670)$  are produced via natural parity exchange, i.e. mainly the  $\rho$  trajectory<sup>7</sup>. The fact that the states also decay to  $\rho\pi$  enables us to make a rough phenomenological estimate of the partial width of the states to  $\rho\pi$ . The number of events observed should be proportional to the coupling of the incoming pion to the exchanged  $\rho$  and the probability of decay of the state  $X$  to  $\rho\pi$ , i.e. to  $|\mathcal{M}|^2(X \rightarrow \rho\pi) BR(X \rightarrow \rho\pi)$ . The amplitude  $\mathcal{M}$  and the width  $\Gamma$  are related by  $|\mathcal{M}|^2 = \frac{8\pi m_X^2}{|q|} \Gamma$  [4], where  $m_X$  is the mass of  $X$  and  $q$  the momentum of  $\rho$  in the rest frame of  $X$ . Hence,

$$\Gamma(X \rightarrow \rho\pi) \propto \sqrt{(\text{Number of events})_X (\text{Total width})_X} \frac{|q|}{m_X^2} \quad (1)$$

<sup>6</sup>The total width of  $2^{+-}$  hybrids are anomalously small in the PSS flux-tube model [16].

<sup>7</sup>Exchange of the  $f_2$  trajectory should be suppressed on mass grounds, and since no significant  $a_2$ ,  $a_1$ ,  $\hat{\rho}(1600) \rightarrow f_2\pi$  was reported (although  $\pi_2(1670) \rightarrow f_2\pi$  was observed) [1]. We also neglect diffractive exchange due to the low acceptance of the experiment at small  $t < 0.1$  GeV<sup>2</sup> [3], although this possibility has not been eliminated experimentally.

We estimate<sup>8</sup>  $R(X) \equiv \Gamma(X \rightarrow \rho\pi)/\Gamma(a_2 \rightarrow \rho\pi)$  according to Eq. 1 from E852 data [1]

$$R(a_1) \approx 2.9 \quad R(\pi_2(1670)) \approx 1.2 \quad R(\hat{\rho}(1600)) = 0.3 - 0.4 \quad (2)$$

while estimates from the PDG gives

$$R(a_1) = 3.4 \quad R(\pi_2(1670)) = 1.1 \quad (3)$$

It is clear that the naïve estimates of  $R(X)$  from E852 data are in accord with expectations from the PDG, motivating the use of Eq. 1. Since  $R(\hat{\rho}(1600)) = 0.3 - 0.4$  we can predict that  $\Gamma(\hat{\rho}(1600) \rightarrow \rho\pi) = 20 - 30$  MeV and  $BR(\hat{\rho}(1600) \rightarrow \rho\pi) = 10 - 20\%$ .

An experimental limit on  $BR(\hat{\rho}(1600)^+ \rightarrow \rho^0\pi^+) \lesssim 20\%$  has been published for a  $1^{-+}$  state at 1.5 GeV [17]. This translates to  $BR(\hat{\rho}(1600) \rightarrow \rho\pi) \lesssim 40\%$ , well within the estimates presented above. Since these limits are not available at 1.6 GeV, we assume that the results remain unchanged. Ref. [17] attempted to put a more restrictive bound on the  $\rho\pi$  coupling of the  $1^{-+}$  by using the assumption that the state only decays to  $\rho\pi$  and  $\eta\pi$ . As we shall see in the next paragraph, this is not a good assumption. Also, a limit of  $\Gamma(\hat{\rho}(1600)^+ \rightarrow \gamma\pi^+) BR(\hat{\rho}(1600)^+ \rightarrow \pi^+\eta) \lesssim 25$  keV has been derived [17], which we translate within the assumption of VDM coupling of the photon to  $\Gamma(\hat{\rho}(1600) \rightarrow \rho\pi) BR(\hat{\rho}(1600) \rightarrow \pi\eta) \lesssim 6$  MeV, using the equations in ref. [17]. This is not very restrictive, and we urge current experiments at BNL and VES which sample  $\eta\pi$  and  $\rho\pi$  couplings at various invariant masses to derive a more restrictive bound, since suppression of  $\eta\pi$  is expected from symmetrization selection rules [15].

VES recently pointed out that changes in the assumptions of their partial wave analysis can eliminate their preliminary claim of the observation of  $\hat{\rho}(1600)$  in  $\rho\pi$  [6]. On the basis of this they exclude the observation of  $\hat{\rho}(1600)$  at the level of

$$\frac{(\text{Number of events})_{\hat{\rho}}}{(\text{Number of events})_{a_2}} \lesssim 0.03 \quad (4)$$

Within the assumptions of Eq. 1 this bound is equivalent to the bound  $BR(\hat{\rho} \rightarrow \rho\pi) \lesssim 10\%$ .

This is not manifestly in disagreement with the branching ratio  $BR(\hat{\rho}(1600) \rightarrow \rho\pi) = 10 - 20\%$  estimated from E852 data.

<sup>8</sup>We estimate 100000, 370000, 60000 and 8000 events in natural parity exchange under the  $a_2$ ,  $a_1$ ,  $\pi(1670)$  and  $\hat{\rho}(1600)$  Breit-Wigner peaks. The total widths used are respectively 107, 250, 258 and 168 MeV and the  $\rho\pi$  widths used are respectively 74, 250, 80 MeV [1, 4].

The non-observation of  $\hat{\rho}(1600)$  in  $\eta\pi$  by VES and BNL [2, 18], and weak evidence for  $\eta'\pi$  coupling at VES [2] suggests that the ordering<sup>9</sup> of partial widths for  $\hat{\rho}(1600)$  is  $\eta\pi < \eta'\pi < \rho\pi$ . If the  $\rho\pi$  branching ratio is 10 - 20%, as calculated above, the question arises what the dominant modes of  $\hat{\rho}(1600)$  are. Since BNL indicated that  $b_1$  and  $f_1$  exchange may be important [1], as previously mentioned, decays to  $b_1\pi$  and  $f_1\pi$  may be dominant.

Is  $\hat{\rho}(1600)$  dominantly a hybrid, four-quark state or glueball?

The pure  $SU(3)$  lattice gauge theory  $1^{-+}$  glueball is predicted at mass  $\leq 4.1$  GeV with high confidence [19]. However, “there is no evidence for any [exotics] of mass less than 3 GeV” [19]. This establishes that the  $1^{-+}$  glueball is distant in mass relative to the  $\sim 2$  GeV mass region we are interested in. A preliminary quenched lattice study found small  $0^{++}$  glueball mixing with pseudoscalar states [20], indicative of weak glueball mixing. We henceforth consider the  $1^{-+}$  to be a linear combination of a hybrid and four-quark state.

The four-quark interpretation is disfavoured by the fact that no stable configurations with  $J^{PC} = 1^{-+}$  have been predicted in models [21], and that the total width is expected to be substantial due to a lack of inhibition for four quarks to “fall apart” to meson final states. If  $\hat{\rho}(1600)$  is a four-quark state, we expect at least two isovector four-quark states in the same mass region [21], since both  $(QQ)_{I=1}(\bar{Q}\bar{Q})_{I=0}$  and  $(QQ)_{I=0}(\bar{Q}\bar{Q})_{I=1}$  are independent degrees of freedom. 50%-50% linear combinations yield two charge conjugation eigenstates with opposite C-parity [21]. Thus if  $\hat{\rho}(1600)$  is a four-quark state, we expect evidence for an isovector  $1^{--}$  at  $\sim 1.6$  GeV.

The molecular interpretation is questionable because  $\hat{\rho}(1600)$  is far from the  $\rho\pi$  threshold it has been detected in. To eliminate this interpretation, lack of coupling of  $\hat{\rho}(1600)$  to threshold channels<sup>10</sup> like  $\rho(1450)\pi$  should be established.

On the other hand, all current information is consistent with the hybrid interpretation:

1. The connected decays of exotic hybrid mesons to  $\eta\pi$  and  $\eta'\pi$  are suppressed by symmetrization selection rules [14], which is consistent with the non-observation of the  $\hat{\rho}(1600)$  in  $\eta\pi$  and the weak  $\eta'\pi$  [2, 18]. Isovector four-quark state decay to  $\eta\pi$  and  $\eta'\pi$  are not necessarily suppressed by symmetrization selection rules, although in cer-

<sup>9</sup>Assuming that the number of events is proportional to  $\Gamma(X \rightarrow \rho\pi) BR(X \rightarrow \eta^{(\prime)}\pi)$ , we make the rough estimates  $BR(\hat{\rho}(1600) \rightarrow \eta\pi) \lesssim 1\%$  from BNL and VES data [2, 18] and  $BR(\hat{\rho}(1600) \rightarrow \eta'\pi) \sim 2\%$  from VES data [2]. If the structure in  $\eta'\pi$  is not taken to be due to the  $\hat{\rho}(1600)$ , we have the upper bound  $BR(\hat{\rho}(1600) \rightarrow \eta'\pi) \lesssim 2\%$ .

<sup>10</sup> $\rho\omega$ ,  $\eta(1440)\pi$ ,  $f_1(1420)\pi$ ,  $f_1(1510)\pi$ ,  $f_2'(1525)\pi$  and  $f_2(1430)\pi$  are near the 1.6 GeV threshold.

tain configurations they can be [14]. Although this does not rule out the four-quark interpretation, it is consistent with  $\hat{\rho}(1600)$  being a hybrid meson.

2. Single OZI forbidden diagrams can lead to flavour SU(3) singlet production, since the pair created out of the vacuum is a flavour singlet within SU(3) symmetry. This enhances  $\eta'\pi$  relative to  $\eta\pi$  if we neglect phase space, since the  $\eta'$  has a large SU(3) singlet component [14, 22]. This is also confirmed by QCD sum rules calculations (as discussed in ref. [14]). All of this is consistent with the claim from VES that  $\eta'\pi > \eta\pi$  when phase space is removed. This is not the expectation for a four-quark state [14, 22].
3. The small  $\rho\pi$  coupling  $BR(\hat{\rho}(1600) \rightarrow \rho\pi) \approx 10 - 20\%$  previously extracted from the data is consistent with model predictions for a hybrid meson<sup>11</sup> [16], where the  $\rho\pi$  coupling is suppressed due to a selection rule [23].

We list promising unexplored production mechanisms for  $\hat{\rho}(1600)$ :

1.  $p\bar{p}$  in the dominant  $^1S_0$  configuration can annihilate to  $\hat{\rho}(1600)\pi$  in P-wave. The decay  $\hat{\rho}(1600) \rightarrow \rho\pi \rightarrow (\pi^+\pi^-)\pi$  can be accessed at Crystal Barrel.
2. Photoproduction of  $1^{-+}$  has provisionally been approved at TJNAF [13] and since diffractive exchange has  $C = +$  and is electrically neutral, the production of  $1^{-+}$  can only be via meson exchange, particularly  $\pi$ ,  $\omega$  and  $\rho$  exchange.

$p\bar{p}$  central production at WA102, FNAL, RHIC and COMPASS and gluon jets at LEP2 can also produce  $\hat{\rho}(1600)$ .

We sketch further production mechanisms for exotics.

$\psi$  radiative decay: The expectation is that  $\Gamma(\text{hybrid} \rightarrow g\bar{g}) \sim \alpha_S$  and that the production of hybrid mesons in  $\psi$  radiative decay should be substantial<sup>12</sup>. BES should search for the isoscalar partner of  $\hat{\rho}(1600)$  particularly in  $\omega\omega$ ,  $\rho\rho$ ,  $K^*K$  and  $a_2\pi$ .

*Diffractive photoproduction:* Naïve estimates suggest that hybrid meson diffractive production by incoming mesons should be enhanced above that of glueballs, conventional mesons and four-quark states, due to the presence  $Q\bar{Q}$  and glue at the production vertex. This is supported by the recent observation by VES of the hybrid meson candidate [16]  $\pi(1800)$  in diffractive production. VES notes that “the wave  $J^P = 0^-$  dominates at low”

$t < 0.08 \text{ GeV}^2$ , indicating diffraction [9]. We hence expect the diffractive production of neutral exotic  $2^{+-}$  hybrids in photoproduction, in analogy to the diffractive process  $\pi N \rightarrow a_1 N$  for which there is experimental indications. Due to s-channel helicity conservation, neutral exotic  $0^{+-}$  can only be produced in electroproduction.

In conclusion, significant experimental and theoretical progress on a  $J^{PC}$  exotic state has been made. Further progress is expected from searches in other decay channels and for other exotics in various production mechanisms.

Helpful discussions with S.-U. Chung, J. Manak, D. Toussaint, D. Weygand and A. Zaitsev are acknowledged. I acknowledge a Lindemann Fellowship from the English Speaking Union.

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<sup>11</sup>Amongst flux-tube models, the IKP model gives  $BR(\hat{\rho}(1600) \rightarrow \rho\pi) = 10\%$  while the PSS model gives  $20\%$  [16].

<sup>12</sup>This has been confirmed in a model calculation for  $J^{PC} = 0^{-+}$  hybrids [24].

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