Exotic Meson Production in BNL Experiment E852

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Abstract. The status of spin-exotic mesons is reviewed. There is now compelling evidence for at least three π_1 states between one and two GeV. Preliminary results from the reaction $\pi^- p \to \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$ show structure in the exotic waves corresponding to $I^G J^{PC} = 0^- 2^{+-}$.

It has long been recognized that gluonic matter in the form of hybrid mesons is allowed by QCD [1]. It has also been suggested that the study of these gluonic states will yield valuable insights into the nature of color confinement [2]. States with manifestly exotic quantum numbers are particularly vital to our understanding of hadron structure because they cannot have the quark-antiquark structure exhibited by most mesons. These spin-exotic mesons do not mix with conventional hadrons. Lattice-gauge calculations show that the lightest of these should be $J^{PC} = 1^{-+}$ states having a mass around 1.9 GeV/c^2 [3]. QCD sum-rule estimates place them slightly lower in mass [4].

A simple model for these exotic mesons is that of an excited tube of gluonic flux attached to a quark-antiquark pair. A vital step in the identification of these states is the observation of unusual decay properties, for example, large decay strength to a pion and a $b_1(1235)$ meson.

Three isovector exotic mesons have recently been discovered. An isovector 1^{-+} state at 1.4 GeV/c^2 was reported in $\eta\pi$ decay [5, 6] and in $\rho\pi$ decay [7]. Another isovector 1^{-+} meson,

$\pi_1(1600)$, was observed in $\rho\pi$ [8], $\eta'\pi$ [9], and $f_1\pi$ [10] decay. The latter experiment also revealed a higher state, $\pi_1(2000)$ [10].

This rich spectrum of exotic mesons is somewhat puzzling; lattice [3] and flux-tube model [11, 12, 13, 14] calculations predict only one low-mass π_1 meson. Glueballs, being pure glue states and hence isoscalar, do not affect the π_1 spectrum [15]. Donnachie [16] and Szczepaniak [17] have proposed dynamical origins for $\pi_1(1400)$ and/or $\pi_1(1600)$. Four-quark configurations may also contribute to spin-exotic mesons [18]. Further progress in understanding these states, as well as gluonic mesons with conventional quantum numbers, depends on achieving a better understanding of their decay properties.

In the flux-tube model the lightest 1^{-+} isovector hybrid is predicted to decay primarily to $b_1\pi$ [11, 12, 13]. The $f_1\pi$ branch is also expected to be large and many other decay modes are suppressed. This suppression is consistent with recent calculations showing $1/N_c^2$ behavior for decays to spin-zero mesons in the large-N_c limit of QCD [19].

Few experiments have addressed the $b_1\pi$ and $f_1\pi$ meson decay channels. The VES collaboration reported a broad 1^{-+} peak in $b_1\pi$ decay [20], and Lee, *et al.* [21] observed significant 1^{-+} strength in $f_1\pi$ decay. In neither case was a definitive resonance interpretation of the 1^{-+} waves possible. Preliminary results from a later VES analysis show excitation of $\pi_1(1600)$ [22]. Significant $b_1\pi$ strength for $\pi_1(1600)$ was also reported [23]. Recently BNL experiment E852 reported a measurement of $f_1\pi$ decay for $\pi_1(1600)$ and $\pi_1(2000)$ [10]. Both states were observed in natural parity exchange.
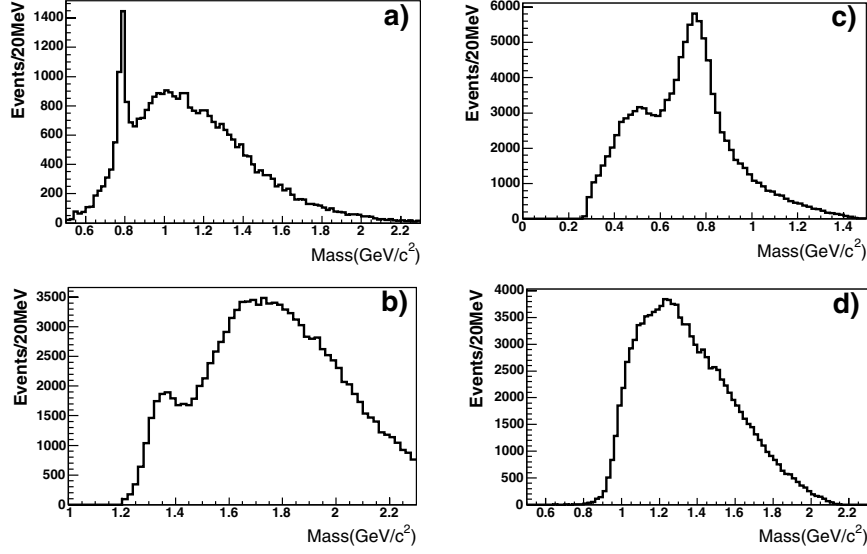
Experiment E852 has recently completed a partial-wave analysis of the reaction $\pi^-p \rightarrow \pi^+\pi^-\pi^-\pi^0\pi^0p$ [24]. Preliminary results have also been obtained for the reaction $\pi^-p \rightarrow \pi^+\pi^+\pi^-\pi^-\pi^0n$.

The data sample was collected during the 1995 run of experiment E852 at the Multi-Particle Spectrometer facility at Brookhaven National Laboratory (BNL). A π^- beam, with laboratory momentum 18 GeV/c, and a liquid hydrogen target were used. A description of the experimental apparatus can be found in Ref. [5].

Data acquisition was triggered on forward-going charged tracks and a signal in a lead-glass electromagnetic calorimeter (LGD). Fiducial cuts were then applied on the target and detector volumes, and a kinematic fit [25] was performed to select events that were consistent with the desired reaction. Events with confidence level greater than five percent were retained. Events that were kinematically consistent with $\eta \rightarrow \pi^+\pi^-\pi^0$ detection were rejected, so as to simplify the partial-wave analysis. Those events with $\pi^+\pi^-\pi^0$ invariant mass near the $\omega(782)$ mass were selected with a mass cut. If more than one mass combination from an event fell in the cut region a random selection was made between the $\omega(782)$ candidates. This process resulted in clean samples of $\omega\pi^-\pi^0$ and $\omega\pi^-\pi^+$ events.

Our result for $\omega\pi^-\pi^0$ decay will be discussed first. Mass plots for those data are shown in Figure 1. Figure 1(a) shows the $\pi^0\pi^-\pi^+$ mass spectrum for a small sample of the data, before $\omega(782)$ selection. All four mass combinations are plotted for each event, showing an undistorted view of the $\omega(782)$ peak. Based on a Monte Carlo simulation of the detector acceptance, we estimate that about 21% of the events that passed the ω mass cut did not have an ω in the final state. Figures 1(b), (c), and (d) show mass distributions after ω selection. Evidence for the $\omega\rho^-$ (Fig. 1(c)) and $b_1\pi$ (Fig. 1(d)) final states is clear. The $\omega\pi^-$ mass distribution (not shown) is similar to that for $\omega\pi^0$. For the final partial-wave fits a further selection was made on the four-momentum transfer to the five-pion system ($0.1 < -t < 1.0$ GeV$^2/c^2$) and meson invariant mass (M ≤ 2.2GeV/c^2). The data follow an $e^{-4.5|t|}$ shape.

A partial wave analysis (PWA) of the present data was made in the isobar model, using the maximum likelihood method [26]. Full rank-2 fits were studied with waves in the range $J \leq 4, L \leq 3$, and $m \leq 1$, where J is total angular momentum, L is the decay orbital-angular momentum, and m is the magnitude of the beam-projection of J. The mass of the $\pi^+\pi^-\pi^-\pi^0\pi^0$
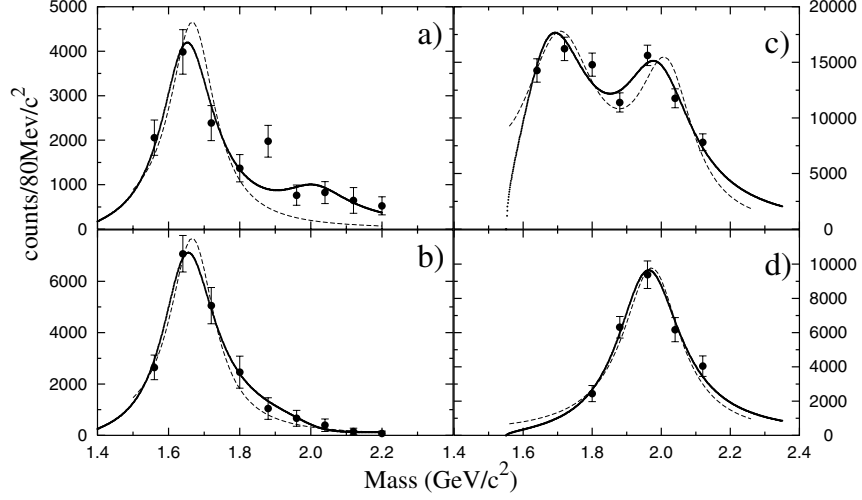
Figure 1. Invariant mass of (a) $\pi^+\pi^-\pi^0$ before the ω mass cut (all combinations), (b) $\omega\pi^0\pi^-$, (c) $\pi^-\pi^0$ using the π^- and π^0 not from the ω, showing $\rho(770)$, and (d) $\omega\pi^0$.
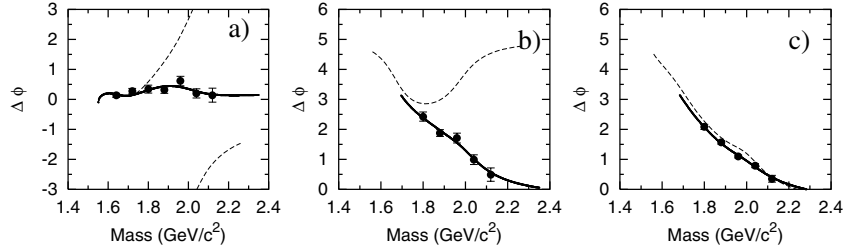
final state was binned in 80 MeV/c^2 intervals and independent fits were performed on the data in each bin. The final state was represented as a sequence of interfering two-body intermediate states. An initial decay of a parent meson into an intermediate resonance (isobar) and an unpaired meson, or two isobars, followed by the subsequent decay of the isobars, populates the final state. The experimental acceptance was determined by means of a Monte Carlo simulation, which was then incorporated into the PWA normalization for each partial wave. The same data selection methods that were used for the experimental data were also applied to the simulated data. Published values were used for the isobar widths [27]. Decays containing more than one charge state for an isobar were constrained to form a single wave with total isospin equal to one. Isovector $\omega\rho$, $b_1\pi$ and $\rho_3(1690)\pi$ waves were sufficient to describe the data.

In addition to these waves an isotropic non-interfering background wave was included at each stage to account for the small waves that were omitted from the fit, as well as the non-ω background. Lastly, a rank-1 fit with the same wave set was compared with the rank-2 result. The wave intensities were similar for the two fits, indicating that a rank-1 approximation was adequate to describe the data. The rank-1 results are discussed below. Mass distributions and angular distributions predicted from the fitted amplitudes are in good agreement with the measured data. In this report we show the results for masses above the $\omega\rho^-$ threshold. The data at lower masses are dominated by $a_2(1320)$ decay (see Figure 1(b)). Further details of the analysis can be found in Ref. [28].

In the final phase of the analysis the PWA results for some of the largest waves were fitted to linear combinations of relativistic Breit-Wigner poles. Mass-dependent resonance widths and Blatt-Weisskopf barrier factors were used. In this fit, shown in Figures 2 and 3, the intensities and phases of the largest 1^{-+}, 2^{++} and 4^{++} waves were fitted, with common resonance parameters in both natural and unnatural parity 1^{-+} waves. Two 1^{-+} poles were included in the fit. The exotic $\pi_1(1600)$ was observed in the $b_1\pi$ channel, and $\omega\rho$ decay was measured for the previously identified $a_2(1700)$, $a_2(2000)$, and $a_4(2040)$ states [27]. The resulting resonance parameters are given in Table 1, with statistical and systematic errors. The quoted resonance widths are the fitted values uncorrected for resolution. The systematic errors were determined by repeating the

Figure 2. Wave intensity for (a) $1^{-+}(b_1\pi)_1^S 1^+$, (b) $1^{-+}(b_1\pi)_1^S 0^-$, (c) $2^{++}(\omega\rho)_2^S 1^+$, and (d) $4^{++}(\omega\rho)_2^D 1^+$. The solid line is the Breit-Wigner result for two 1^{-+} poles and the dashed line is for one.
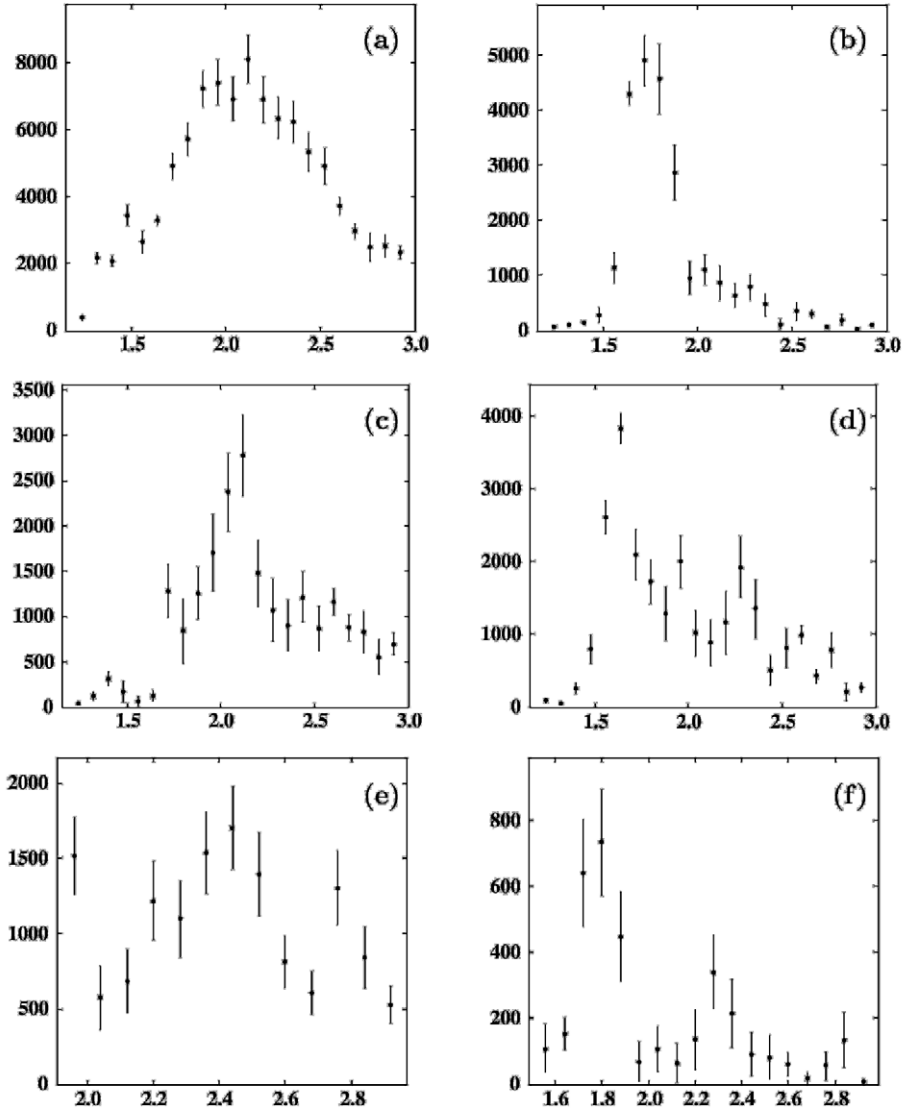

Figure 3. Phase difference for (a) $1^{-+}(b_1\pi)_1^S 1^+ - 2^{++}(\omega\rho)_2^S 1^+$, (b) $1^{-+}(b_1\pi)_1^S 1^+ - 4^{++}(\omega\rho)_2^D 1^+$ and (c) $2^{++}(\omega\rho)_2^S 1^+ - 4^{++}(\omega\rho)_2^D 1^+$. The solid line is the Breit-Wigner result for two 1^{-+} poles and the dashed line is for one.

resonance fits for PWA results with different wave sets and different mass binning, and using an alternative prescription for the mass dependent width [29]. Note that $a_4(2040)$ was observed with a smaller width than expected, and at a lower mass than previously indicated [27]. The width of $\pi_1(1600)$ was measured with higher accuracy than previously and the value, $185\pm25\pm28$ MeV/c^2, is smaller than that observed in $f_1\pi$ [10] and $\eta'\pi$ [9] decay.

This fit also confirms the exotic $\pi_1(2000)$, a state previously discovered in $f_1\pi$ decay [10]. In a fit without the $\pi_1(2000)$ pole, χ^2 increased from 30.7 (for 25 degrees of freedom) to 965 (for 31 degrees of freedom). That result is depicted as the dashed curve in Figures 2 and 3. The mass of $\pi_1(2000)$, M = $2014 \pm 20 \pm 16$ MeV/c^2, is in good agreement with lattice gauge [3] predictions for the lightest spin-exotic meson, as well as flux-tube model estimates for a hybrid meson [11, 14].

The $\pi_1(1600)$ was observed in both natural and unnatural parity exchange, with the largest strength in the unnatural parity wave. However $\pi_1(2000)$ is excited primarily by natural parity exchange. Negligible $\omega\rho^-$ resonance strength was observed for the exotic waves so they were not included in the final fit. A large ratio of $b_1\pi$ to $\omega\rho$ decay strength is expected for a hybrid meson [11, 12, 13]. Thus both $\pi_1(1600)$ and $\pi_1(2000)$ remain as hybrid meson candidates as far
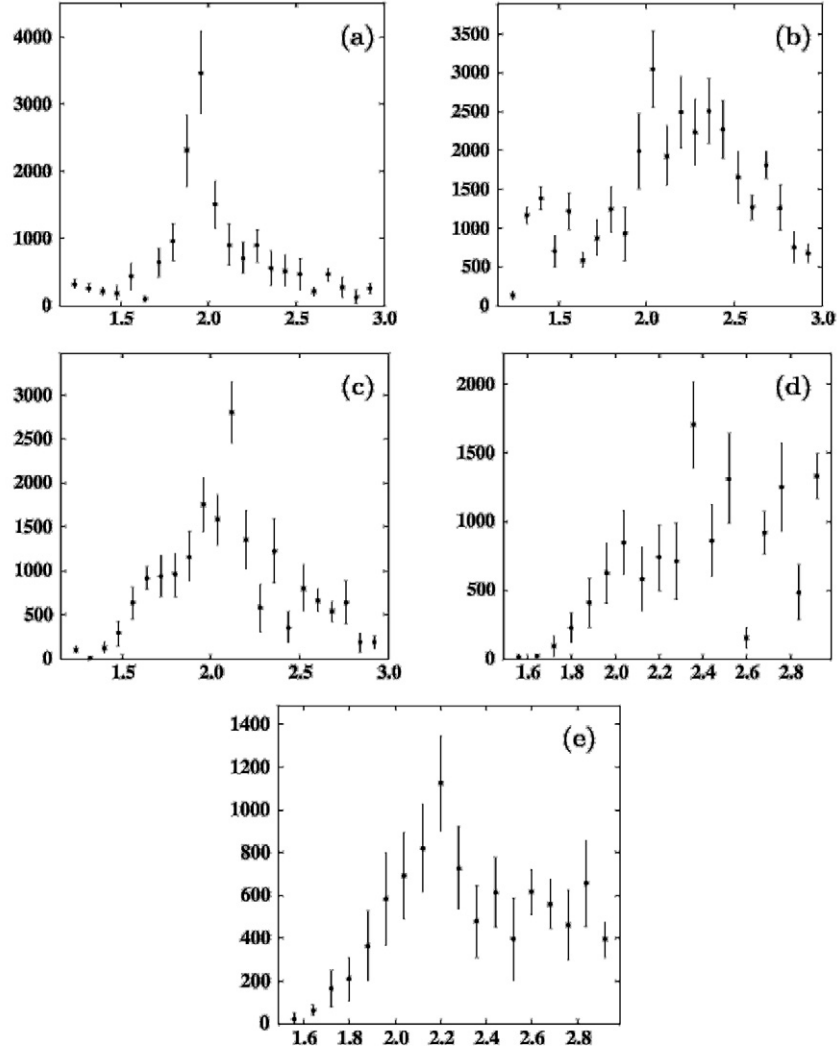
Figure 4. Wave intensity for (a) $I^G J^{PC} = 0^- 1^{--}$, (b) $I^G J^{PC} = 1^- 1^{-+}$, (c) $I^G J^{PC} = 0^- 1^{+-}$, (d) $I^G J^{PC} = 1^- 1^{++}$, (e) $I^G J^{PC} = 0^- 2^{--}$, and (f) $I^G J^{PC} = 1^- 2^{-+}$.

as decay rates are concerned. However $b_1 \pi$ decay is predicted to dominate for hybrid π_1 decay, so one should expect primarily unnatural parity hybrid excitation with pion beams. Therefore the present data favor a hybrid interpretation for $\pi_1(1600)$ based on the excitation mechanism. This result is at odds with the $f_1 \pi$ [10] and $\eta' \pi$ [9] data since $\pi_1(1600)$ was observed only in natural-parity exchange in those cases. Thus the data suggest that two different π_1 states may have been observed at 1.6 GeV/c^2.

Further information on spin-exotic mesons can be obtained from a partial-wave analysis of the data from $\pi^- p \to \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$. Those data were reduced in a similar manner to the charged decays, resulting in a sample of 48k $\omega \pi^- \pi^+$ events. A partial-wave fit using isovector $b_1 \pi$, $\omega \rho$ and $\rho_3 \pi$ waves plus isoscalar $b_1 \pi$, $\omega \sigma$ and $f_2 \omega$ waves was sufficient to describe the data. A total of 32 waves were used, including spin-exotic waves corresponding to $I^G J^{PC} = 1^- 1^{-+}$

Table 1. Resonance parameters. Here the subscript on the measured decay is the coupled intrinsic spin of the isobars.

resonance	decay	mass(MeV/c^2)	width(MeV/c^2)
$a_4(2040)$	$(\omega\rho)_2^D$	$1985\pm10\pm13$	$231\pm30\pm46$
$a_2(1700)$	$(\omega\rho)_2^S$	$1721\pm13\pm44$	$279\pm49\pm66$
$a_2(2000)$	$(\omega\rho)_2^S$	$2003\pm10\pm19$	$249\pm23\pm32$
$\pi_1(1600)$	$(b_1\pi)_1^S$	$1664\pm8\pm10$	$185\pm25\pm28$
$\pi_1(2000)$	$(b_1\pi)_1^S$	$2014\pm20\pm16$	$230\pm32\pm73$

Figure 5. Wave intensity for (a) $I^G J^{PC} = 0^-2^{+-}$, (b) $I^G J^{PC} = 1^-2^{++}$, (c) $I^G J^{PC} = 0^-3^{--}$, (d) $I^G J^{PC} = 0^-3^{+-}$, (e) $I^G J^{PC} = 1^-4^{++}$.

and 0^-2^{+-}. These preliminary results show that exotic waves make up a significant fraction of the total $\omega\pi^-\pi^+$ decay strength. Figures 4 and 5 show the summed intensies for each $I^G J^{PC}$ combination. The $\pi_1(1600)$ is prominent in unnatural parity exchange leading to $b_1\pi$ final states (Fig. 4). Also in evidence is a strong signal at 1.9 GeV in the $I^G J^{PC}=0^-2^{+-}$ waves (Fig. 5). This peak was observed in both natural- and unnatural-parity exchange. It may correspond to a spin-exotic h_2 resonance.

Sufficient experimental evidence has now accumulated to allow one to speculate about the nature of these spin-exotic states. The $\pi_1(1600)$ has a mass of $1664\pm8\pm10$ MeV when observed in $b_1\pi$ decay. This mass is consistent with the value that is expected from QCD sum-rule calculations for a hybrid meson [4]. It is observed as a narrow peak in $b_1\pi$ decay, the decay channel that should dominate for a hybrid π_1 [11, 12, 13]. Lastly, the $\pi_1(1600)$ is excited mainly by unnatural parity exchange. Unnatural parity exchange should be preferred for a state that is produced with a pion beam if it decays predominantly to the $b_1\pi$ channel. This tentative identification of $\pi_1(1600)$ as the lightest spin-exotic hybrid suggests that the $\pi_1(2000)$ is a radial excitation of $\pi_1(1600)$. The h_2 signal observed in $b_1\pi$ decay is also consistent with lattice calculations, which predict 2^{+-} hybrids a few hundred MeV above the 1^{-+} [3, 34]. This leaves the $\pi_1(1400)$, and possibly a natural-parity $\pi_1(1600)$ as potential 4-quark states. Further studies of these exotic mesons in different decay channels and in different production modes should provide a definitive interpretation of their structure.

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