Exotic Meson Decay to $\omega\pi^0\pi^-$

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A partial-wave analysis of the mesons from the reaction $\pi^- p \to \pi^+\pi^-\pi^-\pi^0\pi^0 p$ has been performed. The data show $b_1\pi$ decay of the spin-exotic states $\pi_1(1600)$ and $\pi_1(2000)$. Three isovector 2^{-+} states were seen in the $\omega\rho^-$ decay channel. In addition to the well known $\pi_2(1670)$, signals were also observed for $\pi_2(1880)$ and $\pi_2(1970)$.

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Interest in exotic mesons predates the emergence of quantum chromodynamics (QCD) as the fundamental theory of the strong interaction [1]. With the widespread acceptance of QCD one may hope that a study of gluonic matter will yield 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. 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]. 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 [4,5], and another isovector 1^{-+} meson, $\pi_1(1600)$, was observed in $\rho\pi$ [6], $\eta'\pi$ [7], and $f_1\pi$ [8] decay. This rich spectrum of exotic mesons is somewhat puzzling; lattice [3] and flux-tube model [9,10] calculations predict only one low-mass π_1 meson. Donnachie and Page [11] and Szczepaniak *et al.* [12] have proposed dynamical origins for $\pi_1(1400)$ and/or $\pi_1(1600)$. Four-quark configurations may also contribute to spin-exotic mesons. In the flux-tube model the lightest 1^{-+} isovector hybrid is predicted to decay primarily to $b_1\pi$ [9]. 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 [13]. Recent refinements in the flux-tube calculations cast some doubt on the previous estimates of small π_1 branching widths [14].

Few experiments have addressed the $b_1\pi$ and $f_1\pi$ decay channels. The VES Collaboration reported a broad 1^{-+} peak in $b_1\pi$ decay [15], and Lee *et al.* [16] 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 $\pi_1(1600)$ [17]. A recent experiment measured $f_1\pi$ decay of $\pi_1(1600)$ and $\pi_1(2000)$ [8].

In this Letter, we report an analysis of the reaction $\pi^- p \to \pi^+\pi^-\pi^-\pi^0\pi^0 p$. Partial-wave fits of the mesons from this reaction show the exotic $\pi_1(1600)$ and $\pi_1(2000)$

states in $b_1\pi$ waves. We also observe three isovector 2^{-+} resonances, thus clarifying the spectroscopy of π_2 mesons [18].

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. [4].

Data acquisition was triggered on three forward-going charged tracks, a charged recoil track, and a signal in a lead-glass electromagnetic calorimeter (LGD). A total of 165×10^6 triggers of this type were recorded. After reconstruction, 1.37×10^6 events satisfied the trigger topology and had four photon clusters in the LGD. Fiducial cuts were then applied on the target and detector volumes, and a kinematic fit [19] was performed to select events that were consistent with the reaction $\pi^- p \rightarrow \pi^+\pi^-\pi^-\pi^0\pi^0 p$. Events with confidence level greater than 5% 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 (26% of the sample), a random selection was made between the $\omega(782)$ candidates. This process resulted in a final data sample of 145 148 $\omega\pi^-\pi^0$ events. Mass plots for those data are shown in Fig. 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)–1(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 ($0.1 < -t < 1.0$ GeV2/c^2) and meson invariant mass ($M \leq 2.2$ GeV/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 [20]. 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 $\pi^+\pi^-\pi^-\pi^0\pi^0$ 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 [21]. Decays containing more than one charge state for an isobar were constrained to form a single wave with total isospin equal to one.

Groups of waves were added to the fit in succession, starting with $\omega\rho^-$ and $(b_1\pi)^-$, and small waves were removed at each stage. Isovector $a_1\sigma$, $a_2\sigma$, and $\rho(1450)\pi$ waves were also tested and found to be negligible. The final set of waves is shown in Table I. Isovector $\omega\rho$, $b_1\pi$, and $\rho_3(1690)\pi$ waves are present.

In addition to these waves, an isotropic noninterfering 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. None of the resonance signals

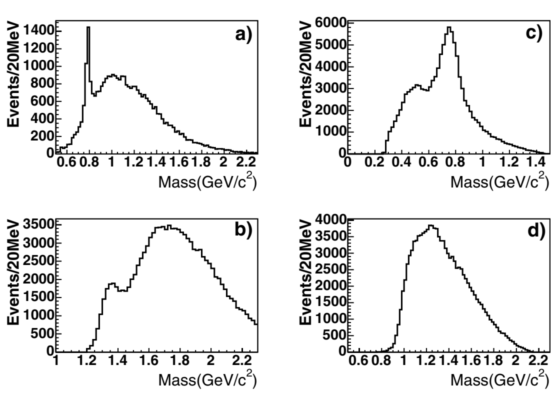

FIG. 1. Invariant mass of (a) $\pi^+\pi^-\pi^0$ before the ω mass cut (all combinations), (b) $\omega\pi^0\pi^-$, (c) $\pi^-\pi^0$ using the π^- and π^0 not from the ω, showing $\rho(770)$, and (d) $\omega\pi^0$.

TABLE I. Waves in the final fit. Here positive ϵ indicates natural-parity exchange and s is the total spin of the initial decay products. An isotropic background wave was also included.

Decay	L	J^{PC}	s	m^ϵ	Decay	L	J^{PC}	s	m^ϵ
$\omega\rho$	S	1^{++}	1	0^+	$b_1\pi$	S	1^{-+}	1	1^+
$\omega\rho$	S	2^{++}	2	0^-	$b_1\pi$	S	1^{-+}	1	1^-
$\omega\rho$	S	2^{++}	2	1^+	$b_1\pi$	S	1^{-+}	1	0^-
$\omega\rho$	P	0^{-+}	1	0^+	$b_1\pi$	P	1^{++}	1	0^+
$\omega\rho$	P	2^{-+}	1	0^+	$b_1\pi$	P	1^{++}	1	1^+
$\omega\rho$	P	2^{-+}	1	1^-	$b_1\pi$	P	2^{++}	1	1^+
$\omega\rho$	P	2^{-+}	2	0^+	$b_1\pi$	P	2^{++}	1	0^-
$\omega\rho$	P	2^{-+}	2	1^+	$b_1\pi$	D	2^{-+}	1	0^+
$\omega\rho$	D	1^{++}	2	0^+	$b_1\pi$	D	2^{-+}	1	1^-
$\omega\rho$	D	1^{++}	2	1^+	$b_1\pi$	D	2^{-+}	1	1^+
$\omega\rho$	D	3^{++}	2	0^+	$b_1\pi$	F	2^{++}	1	1^+
$\omega\rho$	D	4^{++}	2	1^+	$b_1\pi$	F	4^{++}	1	1^+
$\omega\rho$	F	2^{-+}	1	0^+	$\rho_3\pi$	S	3^{++}	3	0^+

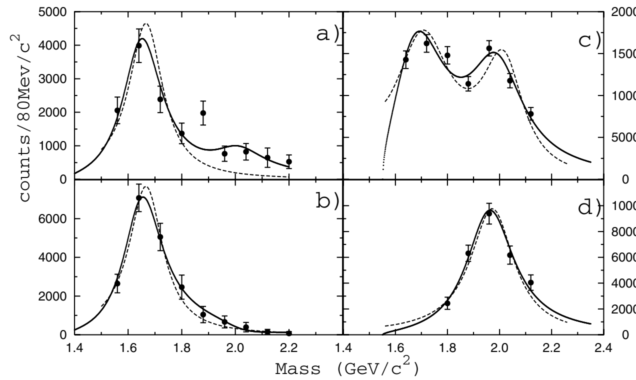

FIG. 2. Wave intensity for (a) $1^{-+}(b_1\pi)_1^S 1^+$, (b) $1^{-+}(b_1\pi)_1^S 0^-$, (c) $2^{++}(\omega\rho)_2^S 1^+$, and (d) $4^{++}(\omega\rho)_2^D 1^+$. The solid line is the Breit-Wigner result for two 1^{-+} poles and the dashed line is for one.

TABLE II. 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)
$a_4(2040)$	$(\omega\rho)_2^D$	$1985 \pm 10 \pm 13$	$231 \pm 30 \pm 46$
$a_2(1700)$	$(\omega\rho)_2^S$	$1721 \pm 13 \pm 44$	$279 \pm 49 \pm 66$
$a_2(2000)$	$(\omega\rho)_2^S$	$2003 \pm 10 \pm 19$	$249 \pm 23 \pm 32$
$\pi_1(1600)$	$(b_1\pi)_1^S$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 28$
$\pi_1(2000)$	$(b_1\pi)_1^S$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$
$\pi_2(1670)$	$(\omega\rho)_{1,2}^P$	$1749 \pm 10 \pm 100$	$408 \pm 60 \pm 250$
$\pi_2(1880)$	$(\omega\rho)_{1,2}^P$	$1876 \pm 11 \pm 67$	$146 \pm 17 \pm 62$
$\pi_2(1970)$	$(\omega\rho)_{1,2}^P$	$1974 \pm 14 \pm 83$	$341 \pm 61 \pm 139$

reported in this Letter are strongly correlated with the intensity of this background wave. 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 Letter, we report the results for masses above the $\omega\rho^-$ threshold. Further details can be found in Ref. [22].

Monte Carlo tests were performed to ensure the significance of the PWA signals described below. Data were simulated using the fitted PWA amplitudes, but with a signal-wave intensity set to zero. Fits using the full set of waves then showed the levels of false signals (''leakage''). These were negligible in all cases.

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 [8]. Two separate fits were performed. In the first fit, shown in Figs. 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 [21]. The resulting resonance parameters are given in Table II, with statistical and systematic errors. The quoted resonance widths are the fitted values uncorrected for resolution. The systematic errors were determined by repeating the resonance fits for PWA results with different wave sets and different mass binning, and using an alternative prescription for the mass-dependent width [23]. Note that $a_4(2040)$ was observed with a smaller width than expected, and at a lower mass than previously indicated [21]. The width of $\pi_1(1600)$ was measured with higher accuracy than previously and the value, $185 \pm 25 \pm 28$ MeV/c^2, is smaller than that observed in $f_1\pi$ [8] and $\eta'\pi$ [7] decay.

This fit also confirms the exotic $\pi_1(2000)$, a state previously discovered in $f_1\pi$ decay [8]. 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 Figs. 2 and 3. The mass of $\pi_1(2000)$, $M = 2014 \pm 20 \pm 16$ MeV/c^2, is in good

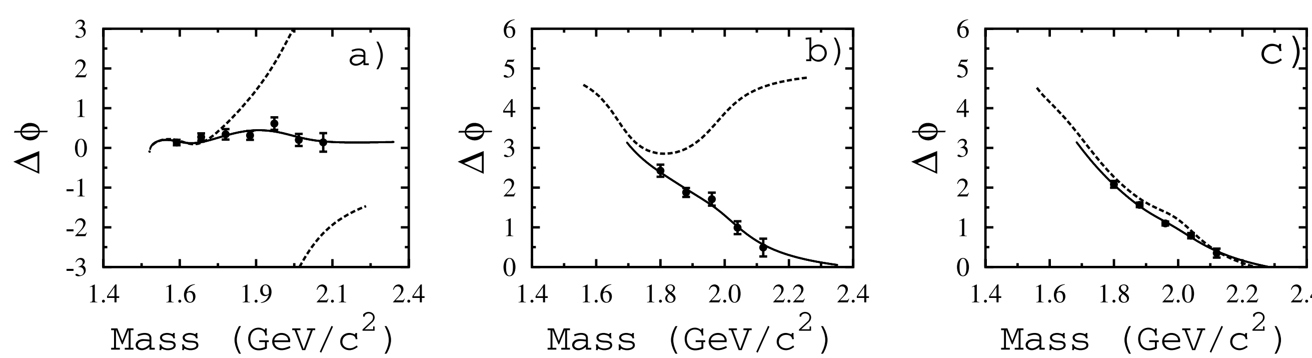

FIG. 3. Phase difference for (a) $1^{-+}(b_1\pi)_1^S 1^+ - 2^{++}(\omega\rho)_2^S 1^+$, (b) $1^{-+}(b_1\pi)_1^S 1^+ - 4^{++}(\omega\rho)_2^D 1^+$, and (c) $2^{++}(\omega\rho)_2^S 1^+ - 4^{++}(\omega\rho)_2^D 1^+$. The solid line is the Breit-Wigner result for two 1^{-+} poles and the dashed line is for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

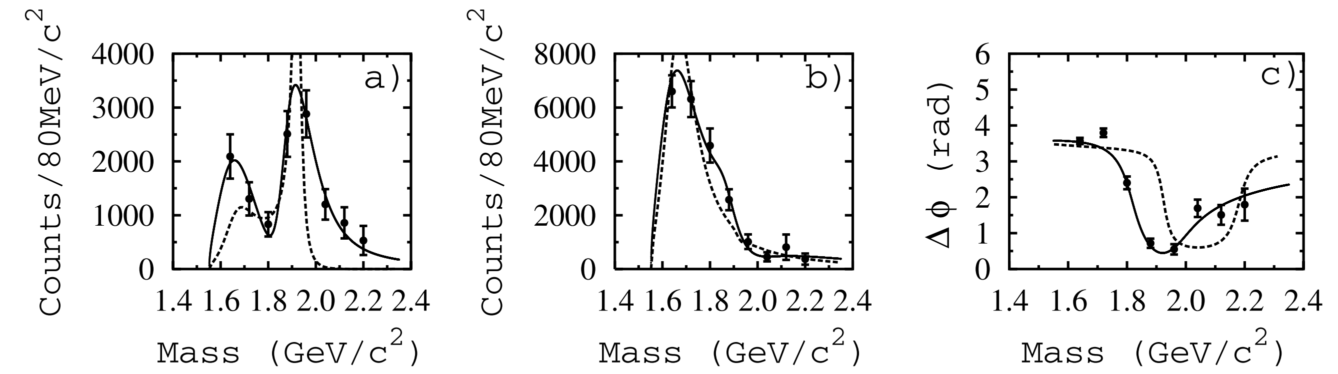

FIG. 4. Wave intensity for (a) $2^{-+}(\omega\rho)_1^P 0^+$ and (b) $2^{-+}(\omega\rho)_2^P 0^+$, and (c) phase difference for (a) minus (b). The solid line is the Breit-Wigner result for three 2^{-+} poles and the dashed line is for two.

agreement with lattice-gauge [3] predictions for the lightest spin-exotic meson, as well as flux-tube model estimates for a hybrid meson [9,10].

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 [9]. Thus both $\pi_1(1600)$ and $\pi_1(2000)$ remain as hybrid meson candidates as far 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 $f_1\pi$ [8] and $\eta'\pi$ [7] 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 (see also Ref. [12]).

The second fit was to the intensities and relative phase of the two largest 2^{-+} waves. Both waves are natural-parity $\omega\rho P$ waves. Three resonance poles were used. The results of the fit are shown as the solid curve in Fig. 4. This fit gave $\chi^2 = 9.0$ for 7 degrees of freedom. Large $\omega\rho$ decay widths were observed for $\pi_2(1670)$ and for $\pi_2(1880)$, a state first observed by Anisovich *et al.* [24]. Our value for the mass of $\pi_2(1880)$, $M = 1876 \pm 11 \pm 67$ MeV/c^2, is in good agreement with the earlier measurement, $M = 1880 \pm 20$ MeV/c^2 [24]. The isoscalar partner of this state, $\eta_2(1870)$, is well known [21]. The presence of $\pi_2(1880)$ in the spectrum prohibits the use of $\pi_2(1670)$ decay as a simple test of hadronic decay models, as proposed by Page and Capstick [25], because there is significant mixing of $\pi_2(1670)$ with $\pi_2(1880)$.

The π_2 fit included a third pole above the $\pi_2(1880)$, yielding $\pi_2(1970)$ with mass $M = 1974 \pm 14 \pm 83$ MeV/c^2 and width $\Gamma = 341 \pm 61 \pm 139$ MeV/c^2. The π_2 data are poorly described in a fit without this resonance, as shown by the dashed curve in Fig. 4. The measured phase difference [Fig. 4(c)] provides a strong constraint on the fit. Alternatively, one could interpret the high-mass data in terms of a rapidly varying production phase for one or both of the waves.

High-lying π_2 strength was reported in several previous experiments. Measurements of $f_1\pi^-$ decay [8] revealed a resonance with mass $M = 2003 \pm 88 \pm 148$ MeV/c^2 and width $\Gamma = 306 \pm 132 \pm 121$ MeV/c^2, in good agreement with the present values. A broad structure was also observed at 2.1 GeV/c^2 in three-pion decay [26]. Those earlier measurements may include contributions from both $\pi_2(1880)$ and $\pi_2(1970)$. Table II lists all of the resonance parameters from the present analysis.

One of the means by which unusual mesons can be identified is to measure a higher density of states than the quark model predicts. In the quark model the $\pi_2(1670)$ is the ground-state 2^- configuration and the first radial excitation is expected at about 2.1 GeV/c^2 [27]. This suggests a conventional meson interpretation for the $\pi_2(1970)$, leaving the $\pi_2(1880)$ as a hybrid meson candidate. A hybrid assignment was first proposed for the $\pi_2(1880)$ based on its large $a_2\eta$ decay strength [24]. Thorough knowledge of the decay properties of $\pi_2(1880)$ and $\pi_2(1970)$ will aid in their identification [9,18]. Further analysis of the present data, including the unnatural-parity π_2 waves listed in Table I, is now underway.

In summary, we observe strong excitation of the exotic $\pi_1(1600)$ in the $(b_1\pi)^-$ decay channel and confirm $\pi_1(2000)$. Three π_2 states were measured between 1.5 and 2.2 GeV/c^2. In addition to the well known $\pi_2(1670)$, we observe $\pi_2(1880)$ and $\pi_2(1970)$ decaying to $\omega\rho^-$. The higher state, $\pi_2(1970)$, is probably a radial excitation, while the $\pi_2(1880)$ may have a large hybrid meson component.

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