Observation of a New $J^{PC} = 1^{-+}$ Exotic State in the Reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c

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A partial-wave analysis of the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c has been performed on a data sample of 250,000 events obtained by Brookhaven experiment E852. The expected $J^{PC} = 1^{++} a_1(1260)$, $2^{++} a_2(1320)$, and $2^{-+} \pi_2(1670)$ resonant states are clearly observed. The exotic $J^{PC} = 1^{-+}$ wave produced in the natural parity exchange processes shows distinct resonance-like phase motion around 1.6 GeV/c^2 in the $\rho\pi$ channel. A mass-dependent fit results in a resonance mass of $1593 \pm 8^{+29}_{-47}$ MeV/c^2 and a width of $168 \pm 20^{+150}_{-12}$ MeV/c^2.

12.39.Mk, 13.25.Jx, 13.85.Hd, 14.40.Cs

Much progress has been made in recent years in the theoretical description of hadrons which lie outside the scope of the constituent quark model. QCD predicts the existence of multiquark $q\bar{q}q\bar{q}$ and hybrid $q\bar{q}g$ mesons as well as purely gluonic states. The most suggestive experimental evidence for an exotic meson would be the determination of quantum numbers $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$,etc. A $q\bar{q}$ pair cannot form a state with such quantum numbers.

Several isovector 1^{-+} exotic candidates have been reported recently. A 1^{-+} signal in the $\eta\pi$ channel has been seen by several groups. Although early measurements [1,2] were inconclusive, the most recent measurements [3,4] have presented strong evidence for a 1^{-+} state near 1.4 GeV/c^2. Another 1^{-+} state with a mass of 1.6 GeV/c^2 was observed in the $\eta'\pi$ [2] and $\rho\pi$ [5] channels. Additionally, a state with resonant phase behavior has been seen above 1.9 GeV/c^2 in the $f_1\pi$ [6] channel.

Theoretical predictions for the mass of the lightest 1^{-+} hybrid meson are based on various models. The flux tube model [7,8] predicts 1^{-+} states at 1.8–2.0 GeV/c^2. Similar results are obtained in the calculations based upon lattice QCD in the quenched approximation [9]. Earlier bag model estimates suggest somewhat lower masses in the 1.3–1.8 GeV/c^2 range [10]. QCD sum-rule predictions vary widely between 1.5 GeV/c^2 and 2.5 GeV/c^2 [11]. The diquark cluster model [12] predicts the 1^{-+} state to be at 1.4 GeV/c^2. Finally, the constituent gluon model [13] concludes that light exotics should lie in the region 1.8–2.2 GeV/c^2. Most of these models predict the dominance of such decay modes of the hybrid meson as $b_1(1235)\pi$ or $f_1(1285)\pi$, with small (but non-negligible) $\rho\pi$ decay probability [14].

In this letter we present experimental evidence for an isovector 1^{-+} exotic meson produced in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$. Experiment E852 was performed at the Multi-Particle Spectrometer facility at Brookhaven National Laboratory (BNL). The experimental apparatus is described elsewhere [3,15,16]. A π^- beam of momentum 18.3 GeV/c and a liquid hydrogen target were used. The trigger was based on the requirement of three forward-going charged tracks and one charged recoil track. Seventeen million triggers of this type were recorded by the experiment during the 1994 run. After reconstruction, 700,000 events with the correct topology remain. Of these, 250,000 events remain after kinematic cuts are applied to insure an exclusive sample of events with a proton recoil.

Figure 1 shows the $\pi^+\pi^-\pi^-$ and $\pi^+\pi^-$ mass spectra. The well-known $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$ resonances dominate the three-pion spectrum. The two-body mass spectrum shows clear evidence for the $\rho(770)$ and $f_2(1270)$ isobars.

A partial-wave analysis of these data was performed using a program developed at BNL [17]. Each event is considered in the framework of the isobar model: an initial decay of a parent particle into a $\pi\pi$ isobar and an unpaired pion followed by the subsequent decay of the isobar. Each partial wave α is characterized by the quantum numbers $J^{PC}[isobar]LM^\epsilon$ — here J^{PC} are spin, parity and C-parity of the partial wave; M is the absolute value of the spin projection on the quantization axis; ϵ is the reflectivity (and corresponds to the naturality of the exchanged particle); L is the orbital angular momentum between the isobar and the unpaired pion.

The spin-density matrix is parameterized in terms of the complex production amplitudes $V_\alpha^{k\epsilon}$ for wave α with reflectivity ϵ [18]. These amplitudes are determined from an extended maximum likelihood fit. The index k corresponds to the different possibilities at the baryon vertex and defines the rank of the spin-density matrix. This rank does not exceed two for the proton-recoil reaction (from proton spin-non-flip and spin-flip contributions). It was determined that a fit with the spin-density matrix of rank one presented here adequately describes the data.

The experimental acceptance was taken into account by means of Monte Carlo normalization integrals as described in [17]. Relativistic Breit-Wigner functions with standard Blatt-Weisskopf factors were used in the description of the $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$ isobars. The $\pi^+\pi^-$ S-wave parameterization was based on the K-matrix formalism [19]. The results presented here were obtained in a fit with the K-matrix parameterization based on the modified "M" solution of [20].

The partial-wave analysis was performed in 40 MeV/c^2 mass bins and for $0.05 < -t < 1.0$ (GeV/c)^2. Goodness-of-fit was estimated by a qualitative comparison of the experimental moments $H(LMN)$ with those predicted by the PWA fit [18]. These moments are the integrals of the $D^L_{MN}(\alpha,\beta,\gamma)$ functions of three Euler angles taken over the experimental or predicted angular distributions. It was determined that a minimal set of 21 partial waves is required in order to achieve a reasonable agreement between the experimental and predicted moments. This set takes into account all relevant decay modes of the known resonances. It includes three 0^{-+} waves, four 1^{++} waves, three 1^{-+} waves, two 2^{++} waves, seven 2^{-+} waves, one 3^{++} wave, and a non-interfering isotropic wave (which turned out to be rather small). The 1^{-+} waves were found to be essential for the description of the moments.

The acceptance-corrected numbers of events for the major non-exotic spin-parity states predicted by the PWA fit are shown in Fig. 2. The $J^{PC} = 1^{++}$ wave corresponding to the $a_1(1260)$ meson is dominant and accounts for almost half of the total number of events in the sample. The $a_2(1320)$ is prominent in the $J^{PC} = 2^{++}$ waves, and the $\pi_2(1670)$ dominates the $J^{PC} = 2^{-+}$ waves. The $J^{PC} = 0^{-+}$ spectrum is quite complex. Its shape below 1.6 GeV/c^2 is very sensitive to the choice of the $\pi^+\pi^-$ S-wave parameterization. Despite this complexity, the $\pi(1800)$ state is clearly seen in the spectrum.

The intensities of the exotic waves are shown in Fig. 3. All three $1^{-+}[\rho(770)]P$ waves with $M^\epsilon = 0^-, 1^-, 1^+$ (denoted as P_0, P_-, and P_+) show broad enhancements in the 1.1–1.4 GeV/c^2 and 1.6–1.7 GeV/c^2 regions. At the same time, the $1^{-+}[f_2(1270)]D1^+$ wave (not shown) is consistent with zero.

The phase difference between the $1^{-+}[\rho(770)]P1^+$ wave and all other significant natural parity exchange waves indicates a rapid increase in the phase of the 1^{-+} wave across the 1.5–1.7 GeV/c^2 region; this is consistent with resonant behaviour. Some of these phase differences are shown in Figs. 4 and 5.

Extensive studies have been made to test the stability of the results with respect to the assumptions made in the analysis. It was found that no significant change in the 1^{-+} waves takes place by inclusion of rank 2 in the spin density matrix, by different choice of the $\pi\pi$ S-wave parameterization, by exclusion of the events from the regions with a relatively large uncertainty in the instrumental acceptance, or by making PWA fits in restricted regions of t.

The impact of the finite resolution and acceptance of the apparatus on the 1^{-+} signal was estimated by the following method. Monte Carlo events were generated in accordance with the spin-density matrix found in the fit of the real data, except for the matrix elements corresponding to the 1^{-+} waves which were set to zero. The Monte Carlo simulation of the instrumental acceptance and resolution was applied to the generated events. Intensities of the 1^{-+} waves found in the partial-wave fit of this sample are shown as shaded histograms in Fig. 3. Considerable leakage from the non-exotic waves to the 1^{-+} waves is evident below 1.4 GeV/c^2. An additional study has identified the $1^{++}[\rho(770)]S0^+$ wave as a primary source of this leakage at small values of the three-pion effective mass. Leakage from the 2^{++} and 2^{-+} waves turned out to be negligible. The presence of leakage prevents us from drawing any conclusion about the nature of the low-mass enhancement in the 1^{-+} spectrum. However, the second peak in the 1^{-+} intensities at 1.6 GeV/c^2 (where resonant behavior is observed) is not affected by the leakage problem.

We have also studied how our results for the exotic 1^{-+} wave are affected by the choice of the partial waves used in the PWA fit. Numerous wave sets ($J \leq 4$, $|M| \leq 1$, with up to 42 waves in a set) were tried in the fits. The resonant phase motion of the 1^{-+} wave was present in all fits, although the magnitude and width of the peak in the 1^{-+} intensity varied. These variations lead to the rather large model-dependent systematic uncertainties which we assign to the parameters of the 1^{-+} state.

To determine the resonance parameters, a series of two-state χ^2 fits of the $1^{-+}[\rho(770)]P1^+$ and $2^{-+}[f_2(1270)]S0^+$ waves as a function of mass was made. The latter wave was chosen as an anchor because it is a major decay mode of the $\pi_2(1670)$, the only well-established resonance in the vicinity of 1.6 GeV/c^2. An example of such a fit is shown in Fig. 5. The χ^2 function of the fit is $\chi^2 = \sum Y_i{}^T E_i{}^{-1} Y_i$, where Y_i is a 3-element vector consisting of the differences between measured and parameterized values for the intensities of both waves and the phase difference between them in the mass bin i, and E_i is a 3×3 error matrix for these values calculated through Jacobian transformation from the error matrix of production amplitudes found in the maximum likelihood fit. Both waves are parameterized with relativistic Breit-Wigner forms including Blatt-Weisskopf barrier factors. In addition to Breit-Wigner phases, a production phase difference which varies linearly with mass is assumed. The fit yields $\chi^2 = 25.8$ for 22 degrees of freedom, with the production phase difference between the two waves being almost constant throughout the region of the fit. If instead the 1^{-+} wave is assumed to be non-resonant (with no phase motion), then the fit has $\chi^2 = 50.8$ for 22 degrees of freedom, and requires a production phase with a slope of 7.6 radians/(GeV/c^2). Such rapid variation of the production phase makes a non-resonant interpretation of the 1^{-+} wave unlikely.

The fitted mass and width of the 1^{-+} state are M=$1593 \pm 8^{+29}_{-47}$ MeV/c^2 and Γ=$168 \pm 20^{+150}_{-12}$ MeV/c^2. The error values correspond to statistical and systematic uncertainties, respectively. The systematic errors were estimated by fitting the PWA results obtained for different sets of partial waves and different rank of the PWA fit.

Unfortunately, there are no significant waves in the unnatural parity exchange sector with which to conduct phase studies of the $1^{-+}[\rho(770)]P0^-$ and $1^{-+}[\rho(770)]P1^-$ waves [see Fig. 3(a)]. Moreover, the absence of interference with a strong wave leads to much greater instability in the magnitude of these small waves in different fits. Nevertheless, the shape of the 1^{-+} intensity distribution in unnatural parity exchange remains comparable with that in natural parity exchange.

In summary, we have performed a partial-wave analysis of the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$. All expected well-known states (a_1, a_2, and π_2) are observed. In addition, the natural parity exchange partial wave with manifestly exotic quantum numbers $J^{PC} = 1^{-+}$ shows structure in the intensity and phase motion which are consistent with a resonance at 1.6 GeV/c^2 decaying into the $\rho\pi$ channel.

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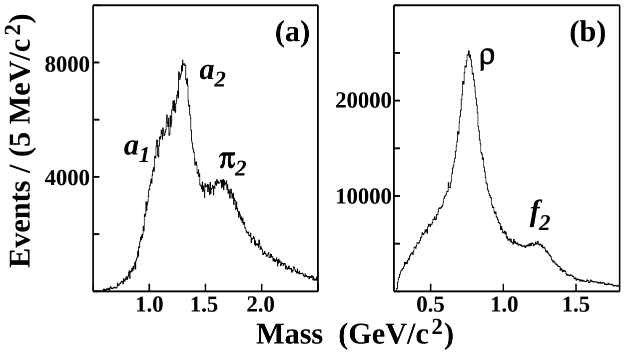

FIG. 1. Experimental effective mass distribution without acceptance correction: (a) $\pi^+\pi^-\pi^-$ mass spectrum, (b) $\pi^+\pi^-$ mass spectrum (two entries per event).

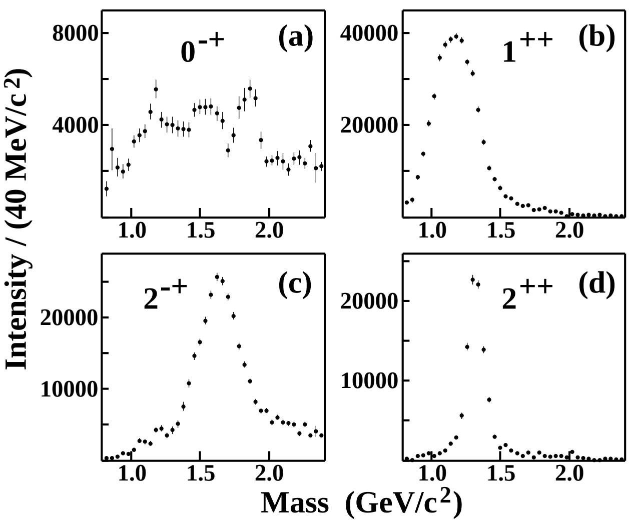

FIG. 2. Combined intensities of all (a) 0^{-+} waves, (b) 1^{++} waves, (c) 2^{-+} waves, (d) 2^{++} waves.

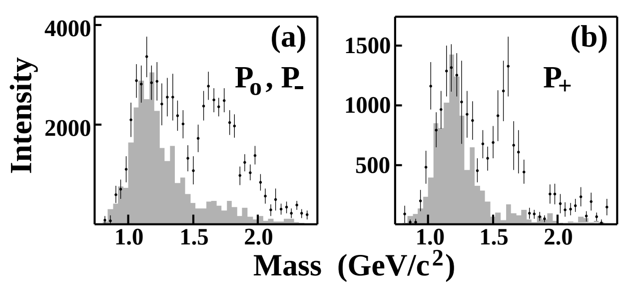

FIG. 3. Wave intensities of the $1^{-+}[\rho(770)]P$ exotic waves: (a) the $M^\epsilon = 0^-$ and 1^- waves combined, (b) the $M^\epsilon = 1^+$ wave. The PWA fit to the data is shown as the points with error bars and the shaded histograms show estimated contributions from all non-exotic waves due to leakage.

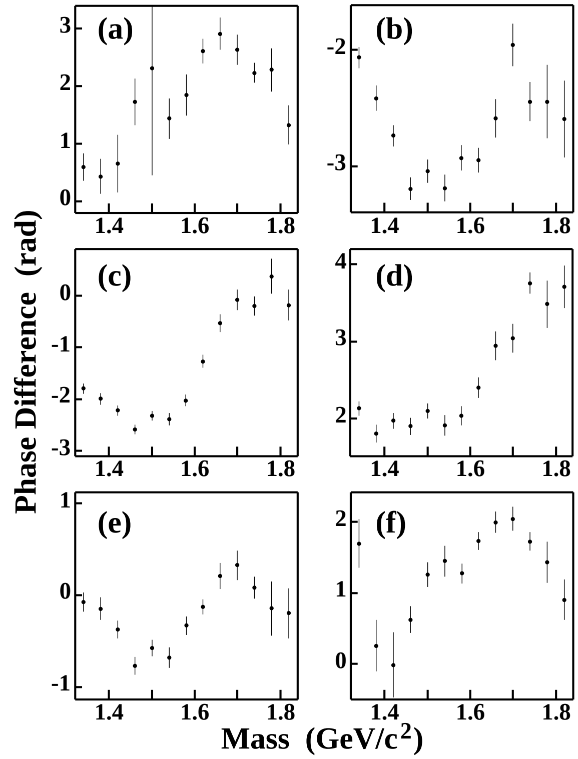

FIG. 4. Phase difference between the $1^{-+}[\rho(770)]P1^+$ wave and (a) the $0^{-+}[f_0(980)]S0^+$ wave, (b) the $2^{++}[\rho(770)]D1^+$ wave, (c) the $1^{++}[\rho(770)]S0^+$ wave, (d) the $1^{++}[\rho(770)]S1^+$ wave, (e) the $2^{-+}[\rho(770)]P0^+$ wave, (f) the $2^{-+}[f_2(1270)]D0^+$ wave.

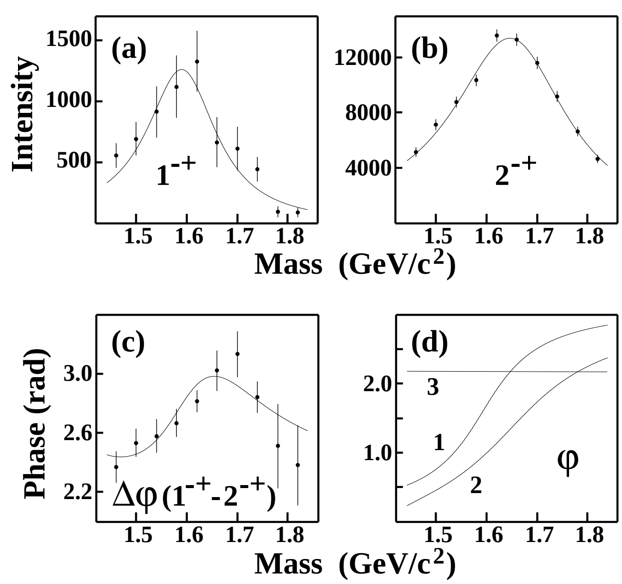

FIG. 5. A coupled mass-dependent Breit-Wigner fit of the $1^{-+}[\rho(770)]P1^+$ and $2^{-+}[f_2(1270)]S0^+$ waves. (a) $1^{-+}[\rho(770)]P1^+$ wave intensity. (b) $2^{-+}[f_2(1270)]S0^+$ wave intensity. (c) Phase difference between the $1^{-+}[\rho(770)]P1^+$ and $2^{-+}[f_2(1270)]S0^+$ waves. (d) Phase motion of the $1^{-+}[\rho(770)]P1^+$ wave (1), $2^{-+}[f_2(1270)]S0^+$ wave (2), and the production phase between them (3).