Spin-parity Analysis of the $f_1(1285)\pi^-$ System in the Reaction $\pi^- p \to f_1(1285)\pi^- p$ at 18 GeV/c

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We have carried out a study of the reaction $\pi^- p \to f_1(1285)\pi^- p$ at 18 GeV/c, with $f_1(1285) \to K^+\bar{K}^0\pi^-$. This reaction is almost entirely mediated by the natural-parity exchange, presumably $f_2(1270)$ or ρ exchange. We find evidence for two possible resonances—a $J^{PC} = 1^{++}$ state at 1.7 GeV/c^2 and a broad $J^{PC} = 1^{-+}$ structure at 1.6–2.2 GeV/c^2.

There is now overwhelming evidence [1] that hadrons exist beyond those predicted in the constituent quark model [2]. However, no unambiguous candidate for such a state has emerged because of the difficulty of distinguishing it from the plethora of hadrons allowed in the quark model. Mesons with $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+} or 2^{+-} would constitute irrefutable evidence for such a state, as a $q\bar{q}$ state cannot couple to them [3]. An isovector state with $J^{PC} = 1^{-+}$, the $M(1405)$, is a prime candidate [4], but its evidence from two recent experiments [5,6] is contradictory. The existence of hybrid mesons has been predicted in a variety of models [7–15]. According to one of these models, the flux-tube model [13], hybrid mesons should not couple strongly to the final states consisting of two ground-state mesons, π and ρ nonets, as the transverse vibrational energy of the excited string cannot be absorbed by them. This selection rule suppresses the $\pi\eta$, $\pi\rho$, $\pi\eta'$ and $K^*\bar{K}$ decay modes of hybrid mesons, and leads them to decay preferentially to the final states containing one orbitally excited meson, e.g., $b_1(1235)\pi$, $f_1(1285)\pi$, $h_1(1170)\pi$ or $a_2(1320)\pi$. The flux-tube model predicts one such state, a 1^{-+} resonance with mass 1.9 GeV/c^2 and width 180 MeV/c^2, decaying into

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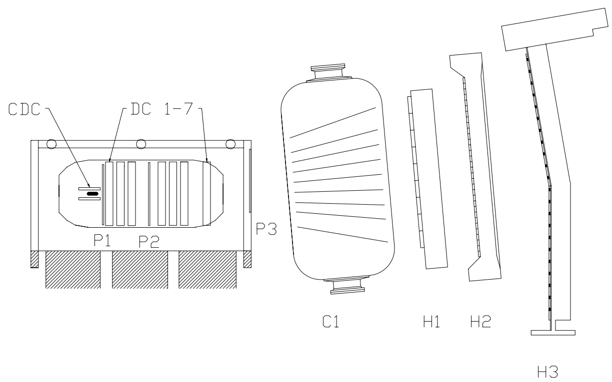

Fig. 1. Schematic diagram of the experimental apparatus. Shown at the center of the magnet is the 30-cm liquid hydrogen target surrounded by cylindrical drift chambers (CDC). P1, P2, and P3 are proportional wire chambers; DC's are drift chamber modules; C1 is a segmented high-pressure Čerenkov counter; H1, H2, and H3 are scintillator-counter hodoscopes.

$b_1(1235)\pi$ and $f_1(1285)\pi$.

The purpose of this experiment has been to look for the I=1, $J^{PC} = 1^{-+}$ state $X^-(1900)$, produced via $b_1(1235)$ exchange, decaying into the $f_1(1285)\pi^-$ final state. The reaction of interest is thus

$$\pi^- p \rightarrow X^- p, \quad X^- \rightarrow f_1(1285)\pi^- \tag{1}$$

where

$$f_1(1285) \rightarrow K^+\bar{K}^0\pi^-, \quad \bar{K}^0 \rightarrow \pi^+\pi^-. \tag{2}$$

This is a particularly attractive channel, since the $f_1(1285)$ is well established experimentally and is narrow, with its width less than 25 MeV/c^2. The data sample was collected with the MPS (Multi-Particle Spectrometer) [16] at the AGS (Alternating Gradient Synchrotron) of Brookhaven National Laboratory.

The layout of the experiment is shown in fig. 1. A tagged π^- beam with its momentum at 18 GeV/c impinged on a 30-cm liquid-hydrogen target within the MPS magnet. The target was surrounded by four cylindrical drift chambers (CDC) [17] which were used to trigger on the recoil proton of reaction (1). Seven drift chamber modules [18], each consisting of seven planes, were used for charged-particle tracking within the MPS magnet (DC1–7). Interspersed among them were three proportional wire chambers (PWC's) (P1, P2, and P3). In addition, a segmented high-pressure Čerenkov counter hodoscope (C1) with $\gamma_{th} = 21.5$, and three scintillation-counter hodoscopes (H1, H2 and H3) were placed downstream of the MPS magnet.

The trigger required a recoil charged particle in the cylindrical drift chambers, three or five charged particles traversing the first PWC (P1=3 or 5) and five charged particles at the second PWC (P2=5), thus including decays between P1 and P2 or in front of P1, (the so-called 1-3-5 and 1-5-5 triggers). It also required a forward-going positive particle traversing C1, H1, H2 and H3 with momentum 3.0 GeV/$c \leq p \leq$ 10.0 GeV/c (as measured on-line by P2, P3, H1, H2, and H3), identified as a K^+ (or proton) by H1$\cdot\overline{\mathrm{C1}}$. The on-line detection of the fast K^+ (or proton) was made through the so-called RAM-trigger, a three-dimensional ($128 \times 128 \times 128$) coincidence matrix system using random-access memory [19].

A total of 1.6×10^7 triggers was recorded in a 1,000-hour run [20]. The beam-flux sensitivity of the experiment was $8.86{\times}10^2$ events/nb. In the present study, only events of the type $\pi^- p \rightarrow K^+\bar{K}^0\pi^-\pi^- p$ have been retained [21]. After event reconstruction, the candidates for the reaction (1) have been selected by requiring:

(1) a K^+ candidate and two negative particles at the production vertex;
(2) a decay vertex at least 2.0 cm downstream of the production vertex; and
(3) a mass at the decay vertex consistent with that of the K_S^0 ($0.48 \leq$m$(K_S^0) \leq 0.52$ GeV/c^2).

In addition, a recoil proton was required by demanding that a track in the CDC be within $\pm 15°$ in the azimuthal view to that predicted by momentum conservation. This requirement effectively suppressed high missing-mass background [17]. These cuts resulted in 2,033 1-3-5 trigger events and 2,893 1-5-5 trigger events. All

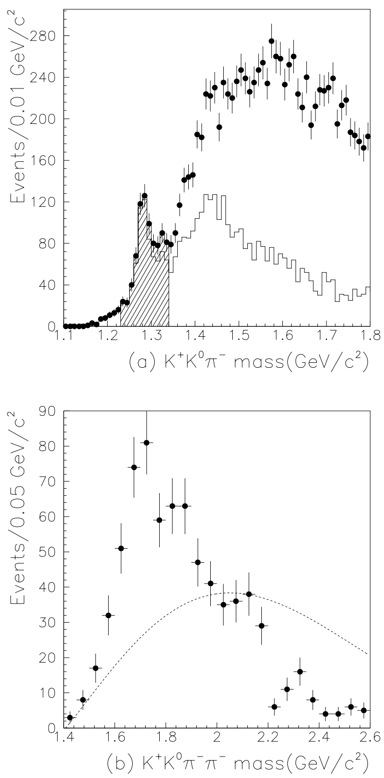

Fig. 2. (a) The $K^+\bar{K}^0\pi^-$ mass distribution. The region for f_1/η selection is shaded. The lower histogram shows the same with an $a_0(980)$ cut. (b) The $K^+\bar{K}^0\pi^-\pi^-$ mass spectrum with an $f_1(1285)$ cut. The dotted line shows the accepted $f_1(1285)\pi$ phase space (see text).

the figures in this letter show the combined data from the 1-3-5 and 1-5-5 triggers.

The $K^+\bar{K}^0\pi^-$ mass distribution (see fig. 2a) shows a prominent peak centered at 1282.2 ± 1.5 MeV/c^2 with a width of 29.0 ± 4.1 MeV/c^2 followed by a rapid rise at the K^*K threshold [the $f_1(1420)$ region]. The same mass spectrum with an $a_0(980)$ cut [m($K\bar{K}$) $\leq$ 1.1 GeV/c^2] shows that the $f_1(1285)$ decay is entirely through the $a_0(980)\pi$ channel. In addition, the $f_1(1420)$ region is seen to be enhanced by this cut. A total of 747 events remain after applying an $f_1(1285)$ cut [$1.235 \leq$ m($K^+\bar{K}^0\pi^-$) ≤ 1.335 GeV/c^2]. In 4 % of the events both π^-'s fall into the $f_1(1285)$ mass region; both combinations were used in the analysis with weighting factors of 0.5. It appears that N^*'s or Δ's play little role in our data; no significant structures are found in the m(π^-p) spectra. The four-momentum transfer distribution has been fitted to a form $e^{-bt'}$ where $t' = |t| - |t|_{\rm min}$; we find $b = 3.9 \pm 0.1$ GeV^{-2} for the t' range $0.15 < t' < 0.65$ GeV^{-2} after acceptance correction. The effective mass of the $K^+\bar{K}^0\pi^-\pi^-$ system [with the $f_1(1285)$ cut] is shown in fig. 2b. A significant enhancement is seen in the spectrum, centered at around 1.7 GeV/c^2 with a strong departure from that expected through phase space. (The phase space events have been generated with a t slope parameter of 3.0 GeV^{-2} and corrected for acceptance.) The mass resolution of the $K^+\bar{K}^0\pi^-$ and $K^+\bar{K}^0\pi^-\pi^-$ systems was determined to be 6.5 MeV/c^2 and 10.6 MeV/c^2, respectively.

A partial-wave analysis (PWA) program [22] of BNL has been used to study the spin-parity structure of the $K^+\bar{K}^0\pi^-\pi^-$ system. This system can be described as a superposition of the states given by J^{PC}, the absolute value of the spin projection M and the naturality of the exchanged particle (or reflectivity) ϵ, collectively denoted M^ϵ, and isobars or intermediate resonances. The present analysis includes two isobars for the primary decay, the $f_1(1285)$ and the $\eta(1295)$ in the $K^+\bar{K}^0\pi^-$ channel, and one for the secondary decay, i.e. the $a_0(980)$ in the $K^+\bar{K}^0$ system. The mass dependent factors of the $f_1(1285)$ and $\eta(1295)$ have been parametrized using the nominal values [23,24], and those of the $a_0(980)$ by the coupled-channel formula of Flatté [25,26,24].

The PWA program, based on the extended maximum likelihood method, was set up to fit the 1-3-5 and 1-5-5 events simultaneously, taking into account the differences in the acceptance and keeping the parameters independent of the numbers of events to first order [22]. The production amplitudes were parametrized according to the prescription given by Chung and Trueman [27]. To maximize the stability of the fits, the data sample was divided into eight overlapping 0.2 GeV/c^2 mass bins at 0.1 GeV/c^2 intervals from 1.5 to 2.4

GeV/c^2.

The wave set used to obtain the final amplitudes was chosen by an extensive iterative search procedure with many different initial sets and starting values. It was found that the most significant and essential state was the 1^{++} wave [28]. We therefore chose the 1^{++} waves as the initial set and added other waves one at a time. Only the waves which significantly improved the likelihood (a change in $\ln \mathcal{L}$ of 4 or more) were retained. We tested waves up to spin 3. The best solutions in each bin were then used to initialize a fit in the adjacent bins. The analysis technique was tested extensively by fitting Monte-Carlo data samples with statistics comparable to the data, generated with various input wave configurations. We also checked the quality of the fits by comparing various experimental distributions with the predicted ones, and found good agreement.

The results of the fit, in the form of the predicted number of events attributed to the spin-parity states, are given in fig. 3. It was found that the states $J^{PC}[\text{isobar}]M^{\epsilon} = 1^{++}[f_1(1285)]0^+$, $1^{-+}[f_1(1285)$ and $\eta(1295)]1^+$, $2^{++}[f_1(1285)]1^+$, all produced via natural-parity exchange, and an incoherent phase-space background wave, were sufficient to describe the data. The high background level (See fig. 3d) is due to the tail of the $f_1(1420)$ ($\sim$ 35 %) and a non-resonant contribution ($\sim$ 15 %) in the data sample. All the other waves turned out to be very small including the spin-zero waves, which can only be produced via unnatural-parity exchange. The $f_1(1285)\pi^-$ decay mode was required for all the waves, and a $\eta(1295)\pi$ decay mode was needed only in the $J^{PC} = 1^{-+}$ wave, contributing $\sim$ 11 % of the total events above the background.

It was pointed out recently that the helicity-coupling amplitudes acquire extra energy-dependent factors beyond those arising from the usual angular-momentum barrier effect because of the requirement of Lorentz invariance [29]. According to this prescription, the $1^{++}[f_1(1285)]$ amplitudes should be multiplied

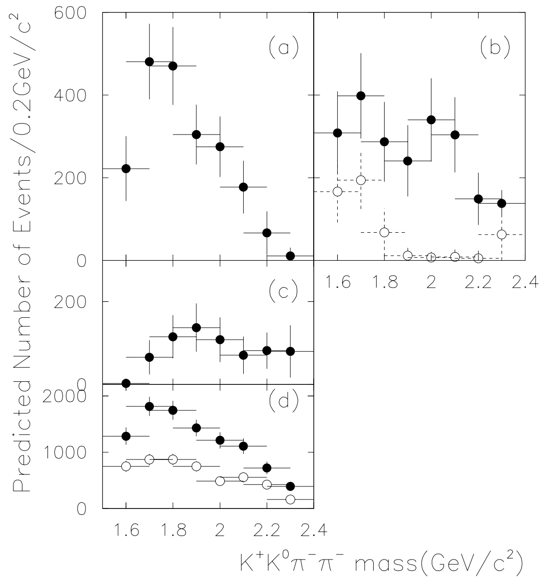

Fig. 3. The partial-wave intensity distributions as a function of $f_1\pi^-$ mass. (a) $J^{PC}M^{\epsilon} = 1^{++}0^+$ wave. (b) $J^{PC}M^{\epsilon} = 1^{-+}1^+$ wave with combined $f_1(1285)\pi$ and $\eta(1295)\pi$ decay modes. The dotted spectrum shows $\eta(1295)$ wave only. (c) $J^{PC}M^{\epsilon} = 2^{++}1^+$. (d) All partial waves included in the fit. The open circles in the plot show the background.

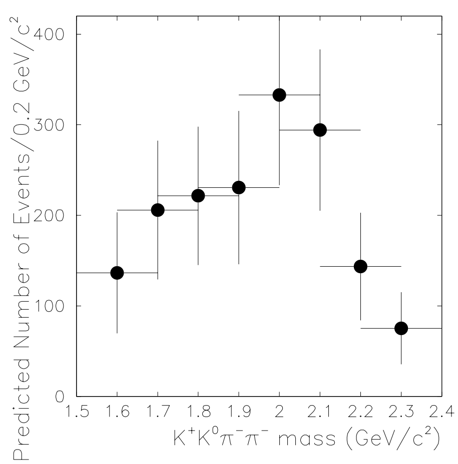

Fig. 4. Predicted number of $1^{-+}[f_1(1285)]1^+$ events as a function of $K^+\bar{K}^0\pi^-\pi^-$ mass.

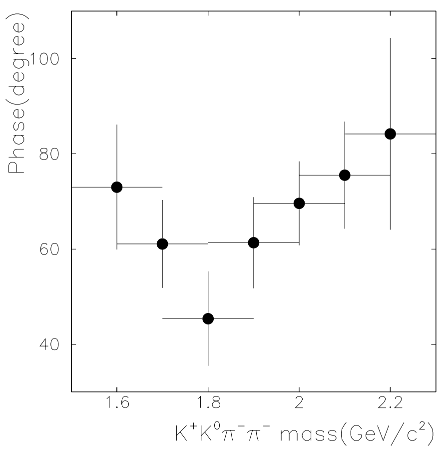

Fig. 5. The relative phase of the $1^{-+}[f_1(1285)]1^+$ wave against the $1^{++}[f_1(1285)]0^+$ wave.

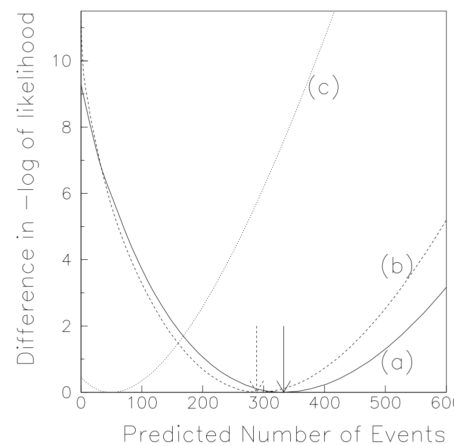

Fig. 6. The difference in $-\ln\mathcal{L}$ as a function of the predicted number of events for $1^{-+}[f_1(1285)]1^+$ wave in the $K^+\bar{K}^0\pi^-\pi^-$ mass interval (a) 1.9–2.1 GeV/c^2 and (b) 2.0–2.2 GeV/c^2. The arrows indicate the minima found by the fits. The curve (c) represents the difference in $-\ln\mathcal{L}$ as a function of the predicted number of events for $1^{-+}[f_1(1285)]0^-$.

by a factor m$(f_1\pi)$, while the $1^{-+}[f_1(1285)]$ and $2^{++}[f_1(1285)]$ amplitudes acquire a factor $E(f_1)/\mathrm{m}(f_1)$—in the rest frame of the $f_1(1285)\pi$ system—if the f_1 helicity is zero. These factors have been tried in our fit; however, the results do not change by more than 15 % throughout all the mass bins when compared to those without the extra factors.

The salient features of the results from PWA on the data are follows:

(1) The data are well described by reflectivity=+ waves only, i.e., the reaction (1) is dominated by natural-parity exchange processes, presumably $f_2(1270)$ or ρ exchange. This is in sharp contrast to our initial expectation for a substantial $b_1(1235)$ exchange.
(2) The ratio of the 1^{-+} wave to total is substantial, at 45 ± 6 %, and it shows a broad structure in the mass region from 1.6 to 2.2 GeV/c^2. This structure is suggestive of being a composite of two objects, at 1.7 and 2.0 GeV/c^2 (see fig. 3b). The 1^{-+} "object" near 2.0 GeV/c^2 is dominated by the $f_1(1285)$ channel (see fig. 4), whereas that at 1.7 GeV/c^2 appears to have a substantial coupling to the $\eta(1295)$ channel. The relative phase of $1^{-+}[f_1(1285)]1^+$ vs. $1^{++}[f_1(1285)]0^+$ is shown in fig. 5. The phase variation could be interpreted as being due to a resonant 1^{++} state at 1.7 GeV/c^2 on a relatively stagnant 1^{-+} phase in this mass region, followed by a resonant 1^{-+} at 2.0 GeV/c^2. However, more data would clearly be required for a firm conclusion. Fig. 6 shows the variation of $-\ln\mathcal{L}$ as a function of the predicted number of 1^{-+} events in the $K^+\bar{K}^0\pi^-\pi^-$ mass intervals 1.9–2.2 and 2.0–2.2 GeV/c^2. It can be seen in this figure that our data definitely require a $1^{-+}[f_1(1285)]1^+$ wave, and inclusion of a $1^{-+}[f_1(1285)]0^-$ wave does not result in significant improvement in the quality of fit.
(3) The J^{PC}=1^{++} wave exhibits a prominent structure centered at 1.7 GeV/c^2 with a rapid rise near $f_1(1285)\pi^-$ threshold (see fig. 3a). The phase motion, as stated in the previous paragraph, is consistent with an interpretation of a 1^{++} resonance at 1.7 GeV/c^2.
(4) The J^{PC}=2^{++} wave shows a broad structure over the mass interval 1.6–2.1 GeV/c^2, but its signal is relatively small.

In summary, we have carried out a study of the reaction $\pi^-p \to f_1(1285)\pi^-p$ at 18 GeV/c, in the decay channel $f_1(1285) \to K^+\bar{K}^0\pi^-$. From a partial-wave analysis we find that this reaction is almost entirely mediated by natural-parity exchange, presumably $f_2(1270)$ or ρ exchange, with two possible resonances: a $J^{PC} = 1^{++}$ state at 1.7 GeV/c^2 and a broad $J^{PC} = 1^{-+}$ structure at 1.6–2.2 GeV/c^2. The 1^{++} state is consistent with the VES results [28] and can be interpreted as a radial excitation of the $a_1(1260)$ at 1.82 GeV/c^2 [30]. The broad 1^{-+} structure shows evidence of a compound system; the structure at 1.7 GeV/c^2 is seen to decay to both $f_1(1285)\pi$ and $\eta(1295)\pi$ channels, whereas that at 2.0 GeV/c^2 decays only via $f_1(1285)$, with a rapid rise in the phase motion observed only in this high-mass region.

The present conclusions are based on limited statistics, and additional data are clearly required for a more complete understanding of the nature of the 1^{-+} wave.

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