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Analysis of the $\eta\pi^0$ System with the Decay $\eta \to \pi^+\pi^-\pi^0$

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The exclusive reaction $\pi^- p \to \eta\pi^0 n$ (where $\eta \to \pi^+\pi^-\pi^0$) at 18 GeV/c has been studied in Brookhaven experiment E852. Mass-dependent and mass-independent partial wave analyses have been performed on a sample of 23,492 $\eta\pi^0 n$ events. The analyses yield consistent resonant parameters for the P_+ wave,providing evidence for a neutral exotic meson with $J^{PC} = 1^{-+}$, a mass of $1.270 \pm 0.014^{+0.080}_{-0.070}$ GeV/c^2 and a width of $0.334 \pm 0.042^{+0.116}_{-0.184}$ GeV/c^2 decaying to $\eta\pi^0$.

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INTRODUCTION

Exotic mesons with quantum numbers $J^{PC} = 0^{--}, 1^{-+}, 2^{+-}, \ldots$ do not mix with quark-antiquark mesons and thus offer a natural testing ground for QCD. Exotic mesons have been discussed [1–10] for many years but have only recently been observed experimentally. The underlying structure of the negatively charged exotic state with $J^{PC} = 1^{-+}$ observed in this experiment [11, 12] at 1400 MeV decaying into $\eta\pi^-$ is not yet understood.

Study of the resonant structure of the neutral $\eta\pi^0$ system near 1400 MeV can be very important in attempting to understand this underlying structure. An important characteristic of the $\eta\pi^0$ system, unlike the $\eta\pi^-$ system, is that C-parity is a good quantum number. The other distinguishing feature is that the production mechanism for the charge exchange reaction $\pi^- p \to \eta\pi^0 n$ cannot involve the exchange of an isospin $I = 0$ system and thus pomeron exchange is ruled out. These characteristics make the $\eta\pi^0$ system an excellent one to clarify the properties of this exotic state.

The Crystal Barrel experiment [13] confirmed the existence of resonant structure in the $\eta\pi^-$ system using stopped antiprotons in liquid deuterium in the reaction $\bar{p}n \to \pi^-\pi^0\eta$. Later this group analyzed the data on $\bar{p}p$ annihilation at rest into $\pi^0\pi^0\eta$ [14] and presented evidence for an exotic 1^{-+} resonance in the $\eta\pi^0$ system with $M = (1360 \pm 25)$ MeV/c^2 and $\Gamma = (220 \pm 90)$ MeV/c^2.

The $\eta\pi^0$ state has been studied in the GAMS experiment [15] using the reaction $\pi^- p \to \eta\pi^0 n$, $\eta \to 2\gamma$, $\pi^0 \to 2\gamma$ at 32, 38 and 100 GeV/c. They showed that the intensity of the P_+ wave has a wide bump at $M = 1300$ MeV/c^2. This structure was difficult to characterize because of the presence of ambiguities in the amplitude analysis. However, the statistics of the 38 GeV/c data was sufficient so that the method of Sadovsky [16] could be used to resolve the ambiguity, and they thus were able to present evidence for the $\pi_1(1400)$ exotic state.

The VES experiment also observed a peak in the P_+ wave of the $\eta\pi^0$ system near 1400 MeV/c^2. See a review of their results in [17]. In their most recent publication [18], using theoretical arguments the authors state that the peak can be understood without requiring an exotic meson.

An analysis of E852 data using the reaction $\pi^- p \rightarrow \eta\pi^0 p$ with decay $\eta \rightarrow 2\gamma$ (instead of $\eta \rightarrow \pi^+\pi^-\pi^0$ considered in this article) was recently reported [19]. A bump in the P_+ wave of the $\eta\pi^0$ system was observed at $M(\eta\pi^0) = 1272$ MeV/c^2 with a large width ($\Gamma = 660$ MeV/c^2) for all regions of t'. Because of the large width and the uncertainties due to the mathematically ambiguous solutions, the authors chose not to claim evidence for exotic $\pi_1(1400)$ meson production.

In the present analysis we have studied the reaction $\pi^- p \rightarrow \eta\pi^0 n$ at 18 GeV/c in E852, using the charged $\eta \rightarrow \pi^+\pi^-\pi^0$ decay. The advantage of this mode over the all-neutral final state is that the production vertex point is defined by charged tracks. This improves the mass resolution as well as the ability to require that the interaction took place in the liquid hydrogen target. We used two independent analyses, one of which is free from the problem of ambiguous solutions. Both analyses give the consistent results.

EXPERIMENTAL SETUP AND DATA SELECTION

The data for this analysis was obtained at the Alternating Gradient Synchrotron (BNL USA). Using an 18 GeV/c π^- beam interacting in a liquid hydrogen target, a total of 750 million triggers were acquired of which 108 million were of a type designed to enrich the exclusive final state $\pi^- p \rightarrow \pi^+\pi^- 4\gamma n$. A total of 6 million events of this type were fully reconstructed. The data were kinematically fitted [20] to select events consistent with the $\pi^-\pi^+\pi^0\pi^0 n$ hypothesis yielding some 4 million events. After a mass cut enhancing η mesons, $m(\pi^-\pi^+\pi^0) < 0.65$ GeV/c^2, we have 85228 events. Following a cut to remove events passing through a low-efficiency region in the drift chambers, we ended up with a sample of 74,549 events of the type $\pi^+\pi^-\pi^0\pi^0 n$. Then the data were kinematically fitted to select 31,679 events consistent with the $\eta\pi^0 n$ hypothesis. Requiring a minimum acceptable confidence level of 1% for this hypothesis, a total of 23,492 $\eta\pi^0 n$ events remained for the partial wave analysis (PWA).

After the cuts described above, a strong η meson signal is observed (see Fig. 1a) with a mass of 539.2 ± 0.3 MeV/c^2 and a width of 23.7 ± 0.22 MeV/c^2. The filled regions in the figure indicate the signal region and the side-band regions used in the analysis. In the η signal region, signal to background ratio is about 6 to 1. The $\eta\pi^0$ mass spectrum shown in Fig.1b has two clear peaks: the $a_0^0(980)$ and the $a_2^0(1320)$.

The non-η background was estimated as a function of $\eta\pi^0$ mass using the side-band and signal regions. The background fraction varies between 24% and 14% going from lower to higher mass in the region $0.78 < m(\eta\pi^0) < 1.74$ GeV/c^2. In the mass region 1.10-1.42 GeV, the anisotropy of the angular distributions of the background events is 25% and 15% for $\cos(\theta_{GJ})$ and φ_{TJ} respectively.

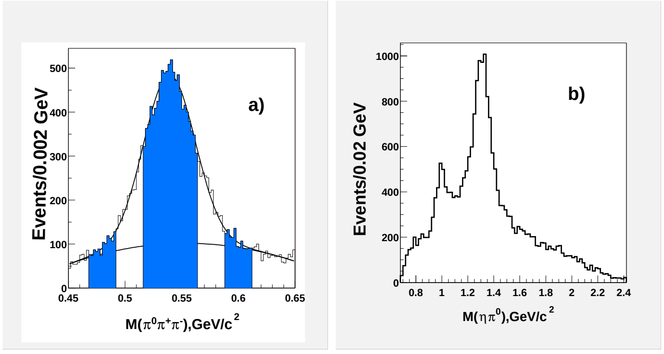

FIG. 1: (a) Fit of the $\pi^+\pi^-\pi^0$ mass distribution (two entries per event) in the η mass region. The η signal region and the side-band regions are shown shaded. (b) The uncorrected $\eta\pi^0$ effective-mass distribution for events consistent with the reaction $\pi^- p \rightarrow \eta\pi^0 n$

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The experimental acceptance was determined using a Monte Carlo event sample. The Monte Carlo events were generated with isotropic angular distributions in the Gottfried-Jackson frame. The detector simulation was based on the E852 detector simulation package SAGEN [12]. The experimental acceptance was incorporated into the PWA by means of Monte Carlo normalization integrals [12]. The acceptance as a function of mass and t' is flat.

MASS-INDEPENDENT PARTIAL WAVE ANALYSIS AND MASS DEPENDENT FIT

A mass-independent partial-wave analysis (PWA) [12, 21, 22] of the data was used to study the spin-parity structure of the $\eta\pi^0$ system. The PWA was carried out using the extended maximum likelihood method separately in each mass bin. The analysis was carried out in the mass region between 0.78 and 1.74 GeV in mass bins of 0.04 GeV for $0 < |t'| < 1.0(GeV/c)^2$ using the likelihood function:

$$\ln\mathcal{L} \propto \sum_{i}^{n} \ln I(\Omega_i) - \int d\Omega \eta(\Omega)\, I(\Omega), \tag{1}$$

where $I(\Omega_i)$ is a predicted angular distribution and $\eta(\Omega)$ is the angular acceptance.

The partial waves are parameterized by a set of five numbers: $J^{PC}m^{\epsilon}$, where J is the angular momentum, P and C are the parity and the C-parity of the $\eta\pi^0$ system, m is the absolute value of the angular momentum projection and ϵ is the reflectivity. We will use simplified notation where each partial wave is denoted by a letter indicating the $\eta\pi^0$ system's angular momentum in standard spectroscopic notation, and a subscript which can take the values 0, +, or $-$, for $m^{\epsilon} = 0^-$, 1^+, or 1^- respectively. We assume that the contribution from partial waves with $m > 1$ is small and can be neglected [12].

The following set of partial waves was used: S_0, P_-, P_0, P_+, D_-, D_0, D_+. The P_+ and D_+ partial waves are natural-parity-exchange partial waves and will be denoted NPW waves. The other waves (S_0, P_-, P_0, D_-, D_0) are unnatural-parity-exchange partial waves and will be denotes as UNPW. We note that the NPW waves interfere between themselves as do the UNPW waves but the NPW waves do not interfere with the UNPW waves.

For each partial wave the complex production amplitudes were determined from an extended maximum likelihood fit [22]. The spin 1/2 nature of the target proton leads to spin-flip and spin-nonflip amplitudes and thus to a production spin-density matrix with maximal rank two. The PWA fit presented in this paper was carried out with the assumption that a spin-density matrix of rank one [12] was sufficient. An isotropic incoherent background was included. The magnitude of the background was fixed as determined from the side bands.

There are discrete mathematical ambiguities in the description of a system of two pseudoscalar mesons [23]. For our set of amplitudes there are eight ambiguous solutions, each of which leads to identical angular distributions.

We investigate the quality of the fits by comparing the moments of the decay angular distributions $H(LM), L \leq 4$, (see [12], [22]) of the data with those predicted by Monte Carlo events generated with the fitted amplitudes. We also directly compare the angular distributions for $\cos(\theta_{GJ})$ and φ_{TJ} between the data and those Monte Carlo events. The quality of the fits is good.

The spreads between the various ambiguous solutions for the UNPW waves are very large as are those for the P_+ wave. These spreads are however relatively small for the D_+ wave and the relative phase between D_+ and P_+ waves. The intensities associated with these waves for the PWA fit are shown as the points with error bars in Fig. 2, Fig. 3 and Fig. 4.

In order to see if the data is consistent with resonant structure in the partial waves, we have carried out a Mass-Dependent Fit (MDF) in the NPW sector. In this fit, rather than attempt to determine which of the ambiguous solutions is "correct", we used an averaging technique [12]. The PWA results in each mass bin were averaged between ambiguous solutions as were the values of the error matrix. Then the mass dependence of the average values of the P_+ and D_+ intensities as well as their relative phase difference were fitted as described below(see Fig.(2)).

The averaged data points were fitted by relativistic Breit-Wigner (BW) functions (in both the P_+ and D_+ waves) with mass-dependent widths and Blatt-Weisskopf barrier factors. In the MDF there are nine free parameters: 6 from two BW functions, one for the (assumed constant) production phase and two parameterizing the smooth background for the D_+ wave (see parametrization in [12]). The resonant hypothesis for $D+$ and $P+$ waves with a mass-independent production phase gives a $\chi^2/DoF = 1.22$. The non-resonant hypothesis (no phase variation for the $P+$ wave) gives $\chi^2/DoF = 3.02$.

Resonant parameters for the fit are given in Table I and the fit is shown as the smooth curves in Fig. 2. We note that the resonant parameters in the D_+ wave are consistent with accepted values for the $a_2(1320)$[24]. (The width of the $a_2(1320)$ includes experimental resolution effects.) The resonant parameters for the P_+ would be for an exotic $J^{PC} = 1^{-+}$ π_1 resonance if the wave is indeed resonant.

The first error in Table I is statistical, determined using the averaged covariance matrix of the mass-independent PWA; the second is systematic. A large number ($\simeq 10^3$) of randomly chosen combinations of ambiguous solutions in each mass bin were used as inputs to the mass-dependent fits. The spreads in the resonance parameters from these fits give us the systematic error range. Also included in the systematic errors is the choice of the mass region used in

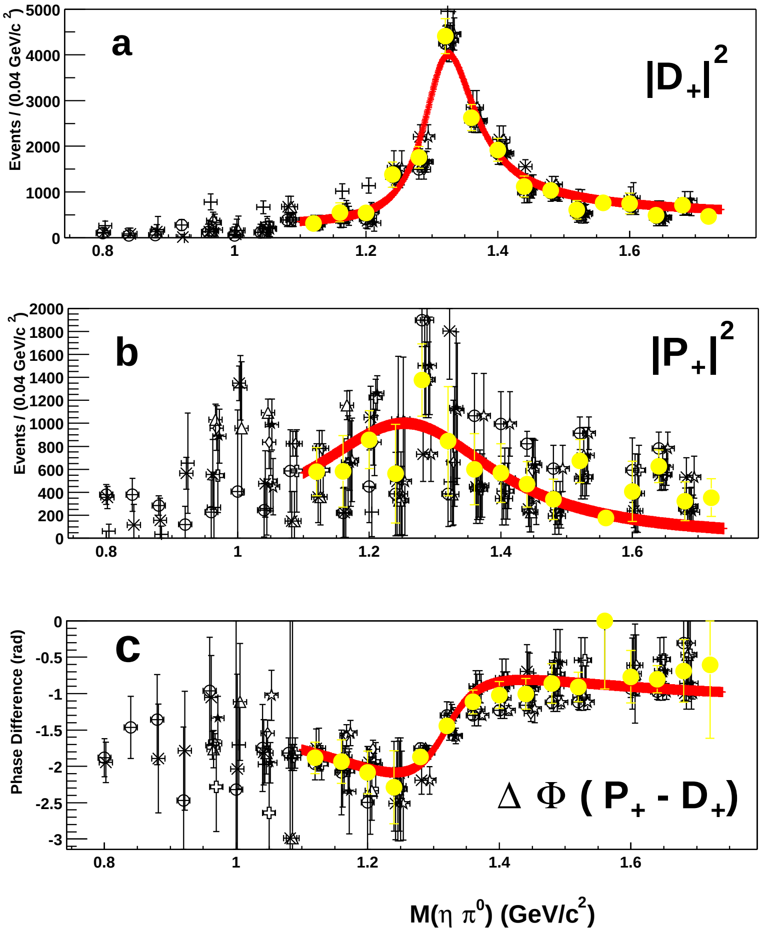

FIG. 2: MDF results (red lines) from fitting the averages of the ambiguous PWA solutions (yellow points with average errors). Fit is in the mass region $1.1 - 1.74$ GeV/c^2. Other points shown are the various ambiguous solutions. a)D_+ wave intensity, b)P_+ wave intensity and c)relative phase of P_+ and D_+ waves.

TABLE I: Fitted BW Resonance Parameters from the MDF analysis

Partial Wave	Mass, MeV/c^2	Width, MeV/c^2
D_+	$1320 \pm 3^{+10}_{-7}$	$96 \pm 3^{+40}_{-15}$
P_+	$1270 \pm 14^{+80}_{-70}$	$334 \pm 42^{+116}_{-184}$

the fitting. For example the change of mass region to a larger interval $0.78 - 1.74$ GeV/c^2 leads to the parameters of the π_1 (mass $= 1273 \pm 17 MeV/c^2$, width $= 412 \pm 57 MeV/c^2$) which are consistent with the values shown in Table I. Our study of the leakage (see discussion below) contribution to the P_+ wave from the D_+ wave shows that it is very small in the MDF.

MASS-DEPENDENT PARTIAL WAVE ANALYSIS

We have carried out a second independent analysis in an attempt to determine the robustness of our results. This second analysis, a so-called Mass-Dependent Partial Wave Analysis (MDPWA) [12] is free from the problem of ambiguous solutions and thus it is not necessary to take an average of ambiguous solutions or to select between them. A potential weakness of the MDPWA is the existence of many free parameters which are needed to parameterize the mass dependence of every wave and all relative phases. In this analysis, the maximum number of free parameters was equal to 22. The MDPWA of the $\eta\pi^0$ system was carried out for $0.78 < m(\eta\pi^0) < 1.74$ GeV/c^2 and $0 < |t'| < 1.0$ (GeV/c)^2.

In the MDPWA the angular distributions are fitted in all $\eta\pi^0$ mass bins simultaneously - see eq. (2). The bins are tied together with a mass-dependent function for each partial wave. The same set of amplitude used in the PWA was used here: S_0, P_0, P_-, D_0, D_- (the unnatural parity waves(UNPW)) and P_+, D_+ (the natural parity waves (NPW)).

In the MDPWA the extended maximum likelihood function is generalized to include not only the angular distribution, but also the $\eta\pi^0$ mass distribution for each wave.

$$\mathrm{ln}\mathcal{L} \propto \sum_i^n \mathrm{ln}I(\Omega_i, m_i) - \int \mathrm{d}\Omega\mathrm{d}m\ \eta(\Omega, m)\, I(\Omega, m). \tag{2}$$

The angular distribution of the $\eta\pi^0$ system is:

$$\begin{aligned} I(m,\theta,\varphi) &= \frac{1}{4\pi}\{\Big|S_0(m) + \sqrt{3}P_0(m)d^1_{00}(\theta) + \sqrt{5}D_0(m)d^2_{00}(\theta) \\ &\quad +[\sqrt{6}P_-(m)d^1_{10}(\theta) + \sqrt{10}D_-(m)d^2_{10}(\theta)]\cos\varphi\Big|^2 \\ &\quad +\Big|[\sqrt{6}P_+(m)d^1_{10}(\theta) + \sqrt{10}D_+(m)d^2_{10}(\theta)]\sin\varphi\Big|^2 \\ &\quad +LK(m,\theta,\varphi)\}\ q(m) \\ &\quad +BG(m). \end{aligned} \tag{3}$$

Here $LK(m,\theta,\varphi)$ is "leakage" into the P_+ wave from the D_+ wave. It has been shown [12] that a pure D+ wave can artificially induce a P_+ signal due to acceptance and resolution effects. Monte Carlo simulation of the E852 resolution shows that this "leakage" leads to a P_+ intensity with the same mass dependence as the D_+ intensity but with a $(P_+ - D_+)$ phase difference which is independent of mass. In addition, the relative phase between the P_+ wave and the leakage amplitude is close to 90°, and thus can be treated incoherently. These features allow us to introduce a term describing leakage $LK(m,\theta,\varphi)$ which has the mass and phase dependence of the $a_2(1320)$ wave.

$$LK(m,\theta,\varphi) \;=\; \mid P_{lk}(m) \mid^2 [\sqrt{6}d^1_{10}(\theta)\sin\varphi]^2. \tag{4}$$

$P_{lk}(m)$ has the D_+-wave mass dependence with its own normalization factor a_{lk}.

$$P_{lk}(m) = a_{lk}\cdot\frac{D_+(m)}{a_2}. \tag{5}$$

In eq. (3), $q(m)$ is the $\eta\pi^0$ break-up momentum and $BG(m)$ is a smooth and isotropic background term, which is calculated and fixed using the side band regions shown in Fig. 1a. The mass dependences of the D_+, P_+, and S_0 amplitudes are assumed to follow Breit-Wigner forms given by:

$$\begin{aligned} P_+(m) &= a_1\Delta(m, m^0_1, \Gamma^0_1)B_1(q)e^{i\ \alpha_1}; && (6)\\ D_+(m) &= a_2\Delta(m, m^0_2, \Gamma^0_2)B_2(q)[1 + b_1(m - m^0_2) + b_2(m - m^0_2)^2]^{1/2}; && (7)\\ S_0(m) &= a_0\Delta(m, m_0, \Gamma_0). && (8)\\ & && (9) \end{aligned}$$

Here the Breit-Wigner amplitude $\Delta(m, m_k, \Gamma_k)$ is given by

$$\Delta(m, m_k, \Gamma_k) \;=\; \frac{m^0_k\cdot\Gamma^0_k}{(m^2 - (m^0_k)^2) + i(m^0_k\Gamma_k(m))} \;=\; e^{i\phi_k(m)}\left|\Delta(m, m^0_k, \Gamma^0_k)\right|, \tag{10}$$

where $\phi_k(m)$ is the Breit-Wigner phase; the widths $\Gamma_k(m)$ are well-known functions of mass, which are proportional to a parameter Γ^0_k and to a Blatt-Weisskopf barrier factor B_i (see [12]); and α_1 is the relative production phase between the $P_+(m)$ and $D_+(m)$ waves.

For the small UNPWs we fitted using various mass dependences $W(m)$. The polynomials of second order and the polynomial-exponential mass dependences tried are given by

$$\begin{aligned} W_1(m) &= a(1 - (m - b)^2/(m - m_{th})^2)e^{i\varphi} && (11)\\ W_2(m) &= a(m - m_{th})(1 + b(m - m_{th}))e^{i\varphi}; && (12)\\ W_3(m) &= a(m - m_{th})^2e^{-b(m-m_{th})}e^{i\varphi} && (13) \end{aligned}$$

TABLE II: Fitted BW Resonance Parameters from the MDPWA.

Partial Wave	Mass, MeV/c^2	Width, MeV/c^2
D_+	$1314 \pm 3^{+13}_{-10}$	$112 \pm 5^{+45}_{-18}$
P_+	$1286 \pm 11^{+40}_{-80}$	$532 \pm 46^{+190}_{-213}$

Here m is the $\eta\pi^0$-mass and $m_{th} = m_{\pi^0} + m_\eta$ is the threshold mass. Note that these functions insure that the wave intensity goes to zero at the threshold mass. Parameters a, b, and φ are free parameters which were different for each wave.

We made many fits with different shapes (eqs. 11- 13) for the UNPW's mass dependences. For all of the fits, we used the same form for the NPW's: $P_+(m)$ (6), $D_+(m)$ (7) and $S_0(m)$ (8). One fit used resonant shapes (10) for all waves. This fit was not satisfactory. In other fits the $D_0(m)$ wave was parameterized with a smooth mass dependence (11)-(13) or as a resonant shape with the same mass and width as $D_+(m)$:

$$D_0(m) \ = \ a_{D_0} \frac{D_+(m)}{a_2} e^{i\varphi_{D_0}} \tag{14}$$

Minima of the likelihood function for all fits were similar. We present in Table II the result of the best fit which corresponds to the polynomial parametrization $W_1(m)$ for the P_0, P_-, and D_- waves and with the D_0 wave fitted as a resonance (eq. 14). The contribution to the P_+ wave due to leakage from the D_+ wave is $|a_{lk}|/|a_1| = 0.17 \pm 0.02$.

Results of the MDPWA are presented as the smooth curves in Fig. 3 and Fig. 4. Also shown for comparison are the results (with all ambiguous solutions) of the mass independent PWA. Note that the smooth curves in Fig. 3 and Fig. 4 are not fitted to the data points in these figures. It is clear from Fig. 3c that a single resonant phase for the $a_2(1320)$ (dotted line) with a constant (non-resonant) P_+ wave is not satisfactory.

The systematic errors for the D_+ and P_+ resonance parameters given in Table II are determined from the spread in the resonance parameters between the fits with different assumptions about the UNPW mass dependences. Note that the parameters from the MDF analysis given in in Table I and those from the MDPWA analysis given in Table II are consistent within errors.

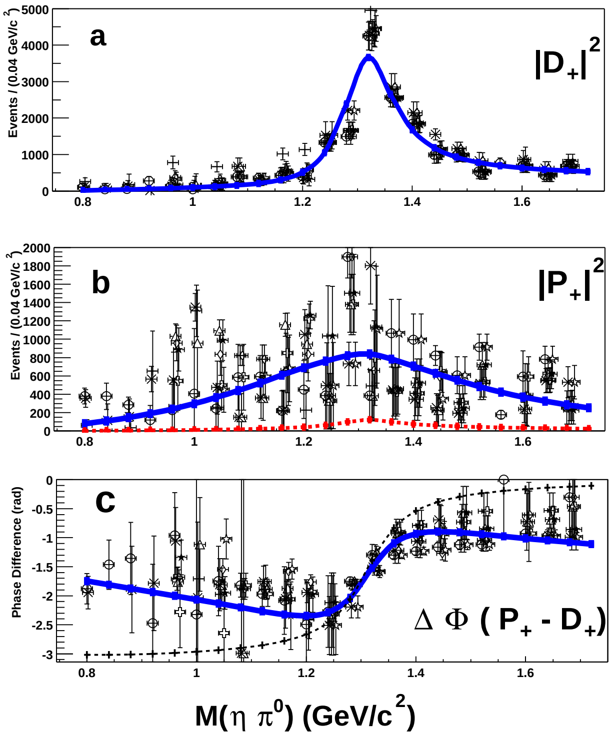

FIG. 3: The results of the MDPWA for the $D+$ and $P+$ waves and the phase difference between them. a) D_+ wave intensity, b) P_+ wave intensity with a leakage contribution (dotted line), and c) the relative phase $(P_+ - D_+)$. The dotted line in (c) is the D_+ phase if there is no P_+ phase variation.

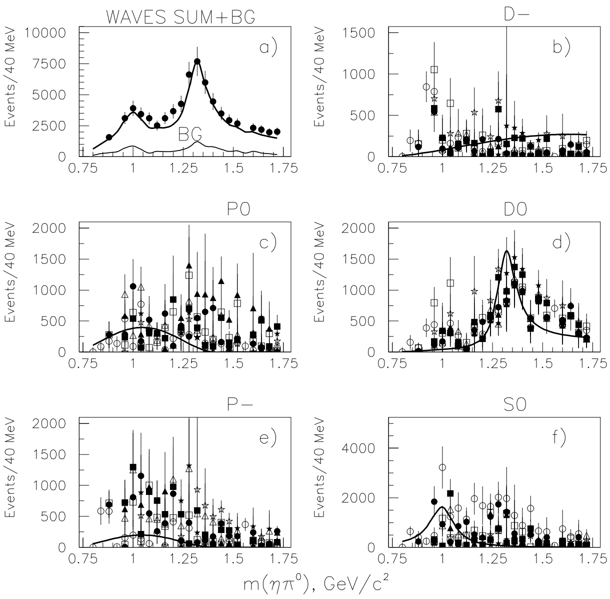

FIG. 4: The results of the MDPWA for the unnatural parity waves. a) A sum of all waves and the background intensity, BG, b) D_- wave intensity, c) P_0 wave intensity, d) D_0 wave intensity, which was fitted with the same BW resonant parameters as the D_+ wave, e) P_- wave intensity, and f) S_0 wave intensity. The P_0, P_-, and D_- waves were fitted by a 2nd order polynomial with a constant phase.

CONCLUSION

A partial wave analysis of data (23,492 events) collected in experiment E852 from reaction $\pi^- p \to \eta\pi^0 n$ (where $\eta \to \pi^+\pi^-\pi^0$) at 18 GeV/c was performed. Two analyses (MDF and MDPWA) of the $\eta\pi^0$ mass dependence give consistent results for an exotic $\pi_1(1400)$ meson with resonant parameters close to the results published earlier. In the MDPWA, it is not necessary to select a “correct” solution among the mathematically ambiguous solutions. Evidence in favor of a resonance interpretation for the P_+ wave is the behavior of the $P_+ - D_+$ phase difference (Fig.3c)and the difference in $\chi^2/DoF = 1.22$ and 3.02 between the resonant and non-resonant nature of P_+ wave

The ratio of the P_+ and D_+ intensities in the range $1.24 < M(\eta\pi^0) < 1.34$ GeV is equal to $|P_+|^2/|D_+|^2 = 0.43 \pm 0.10$. This ratio is larger than that for the $\eta\pi^-$ system [12].

The mass of the neutral exotic 1^{-+} state, decaying into $\eta\pi^0$, observed here (1270 MeV) is lower than the mass observed in the Crystal Barrel experiment (1360 MeV) by about 100 MeV although the results are consistent within errors. If in the future our result with a lower mass is confirmed, then the reason may be as a consequence of interference between the resonant state and background in the $\eta\pi^0$ system. A source of the background in the $\eta\pi^0$ system may be rescattering between the η and the π^0. Another interpretation is that this exotic state may belong to a four quark decuplet of SU(3) with a particular mixing angle.

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