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. The partial wave analysis have been performed on a sample of 23 492 $\eta\pi^0 n$ events. The results of mass dependent fit consistent to the resonant hypothesis with parameters for the P_+ wave, providing evidence for a neutral exotic meson with $J^{PC} = 1^{-+}$, a mass of $1257 \pm 20 \pm 25$ MeV/c^2 and a width of $354 \pm 64 \pm 60$ MeV/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 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 [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 $\pi^-p \to \eta\pi^0 p$ (with $\eta \to 2\gamma$) 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 the whole region of t'. Because of the strong t' dependence of the P_+ resonant parameters, the authors chose not to claim evidence for exotic $\pi_1(1400)$ meson production.

In the present analysis we have studied the reaction $\pi^- p \to \eta\pi^0 n$ at 18 GeV/c in E852, using the charged $\eta \to \pi^+\pi^-\pi^0$ 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.

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 $\pi^- p \to \pi^+\pi^- 4\gamma n$. A total of 6 million events of this type were fully reconstructed. The data were kinematically fit [20] to select events consistent with the $\pi^-\pi^+\pi^0\pi^0 n$ hypothesis (with a confidence level of at least 0.01%) yielding about 4 million events. Of those, 85 228 events passed a mass cut enhancing η mesons, $m(\pi^-\pi^+\pi^0) < 0.65$ GeV/c^2, and 74 549 passed a cut to remove events passing through a low-efficiency region in the drift chambers. A final kinematic fit selected 23 492 events for the partial wave analysis (PWA), which were consistent with the $\eta\pi^0 n$, $\eta \to \pi^+\pi^-\pi^0$ hypothesis at a minimum confidence level of 1%. A strong η meson signal is observed in this final data sample (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, the 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.

The experimental acceptance was determined using a Monte Carlo event sample 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.

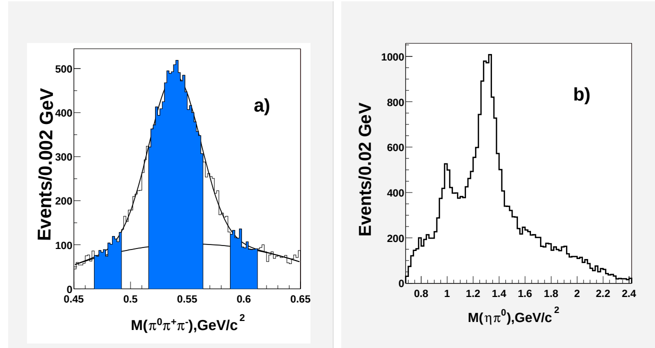

FIG. 1: (a) Fit of the $\pi^+\pi^-\pi^0$ mass distribution in the η mass region. There are two entries per event: one for each way to assign a π^0 to the η decay. The η signal region and the side-band regions are shown shaded. (b) The uncorrected $\eta\pi^0$ effective-mass distribution for events consistent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

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PARTIAL WAVE ANALYSIS

The partial-wave analysis (PWA) method described in [12] (see also [21, 22]) was used to study the spin-parity structure of the $\eta\pi^0$ system in this data set. The PWA was carried out using the extended maximum likelihood method separately in each mass bin 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

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

where $I(\Omega)$ is the predicted angular distribution, $\eta(\Omega)$ is the angular acceptance, and the sum is over the event sample.

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 use a 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 amplitudes used are the unnatural parity-exchange waves (UNPW) S_0, P_0, P_-, D_0, D_-, and the natural parity-exchange waves (NPW) P_+, D_+. The NPW waves interfere between themselves as do the UNPW waves but the NPW waves do not interfere with the UNPW waves. The P_+ wave would be an exotic $J^{PC} = 1^{-+}$ π_1 if the wave is resonant.

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-non-flip 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 was sufficient [12]. An isotropic incoherent background was included. The magnitude of the background was fixed as determined from the side bands. We investigate the quality of the fits by comparing the moments of the decay angular distributions $H(LM), L \leq 4$ [12, 22], of the data with those predicted by Monte Carlo events generated with the fit 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.

Since natural-parity exchange (NPE) and unnatural-parity exchange (UNPE) amplitudes have different $|t'|$ dependence, a fit to a function of the form $N(t') = n_1|t'|e^{-b_1|t'|} + n_2 e^{-b_2|t'|}$ was carried out to determine the relative contributions of the two contributions. The fitted parameters are $b_1 = (7.41 \pm 0.08)(\mathrm{GeV/c})^2$, $b_2 = (2.68 \pm 0.07)(\mathrm{GeV/c})^2$, A ratio of UNPE and NPE contributions is equal to 0.71 ± 0.03. A value about 70% for the ratio of UNPE to NPE is expected in the Regge model at 18 GeV/c.

AMBIGUOUS SOLUTIONS

There is mathematical ambiguity in the description of a system of two pseudo-scalar mesons [23]. For our set of amplitudes there are eight ambiguous solutions, each of which leads to identical angular distributions. These solutions were found analytically starting from one of them by means of the Barrelet zeros method [22]. The spreads between the various ambiguous solutions gives the main contribution in the uncertainty in the resonance parameter determination. To find the physical solution among the ambiguous solutions or at least to diminish the uncertainty in the resonance parameters the additional physical information should be introduced in the analysis. One usually uses the predicted by Regge-pole model behavior of the ratio of the D_- and D_0 wave intensity to the D_+ intensity [23] and the line-shapes of well established resonances [19]. In our case the statistical errors are large and the ratios for different solutions overlap, the only way to decrease the number of ambiguous solutions was to select the solutions which correspond to the good fits of the $a_2^0(1320)$. In the fitting procedure described below the mass and width (including the experimental resolution) of a_2^0 was taken from [24]: $M = 1320$ MeV/c^2, $\Gamma = 120$ MeV/c^2 and fixed in our procedure. The width of $a_2(1320)$ is taken with account of the experimental mass resolution.

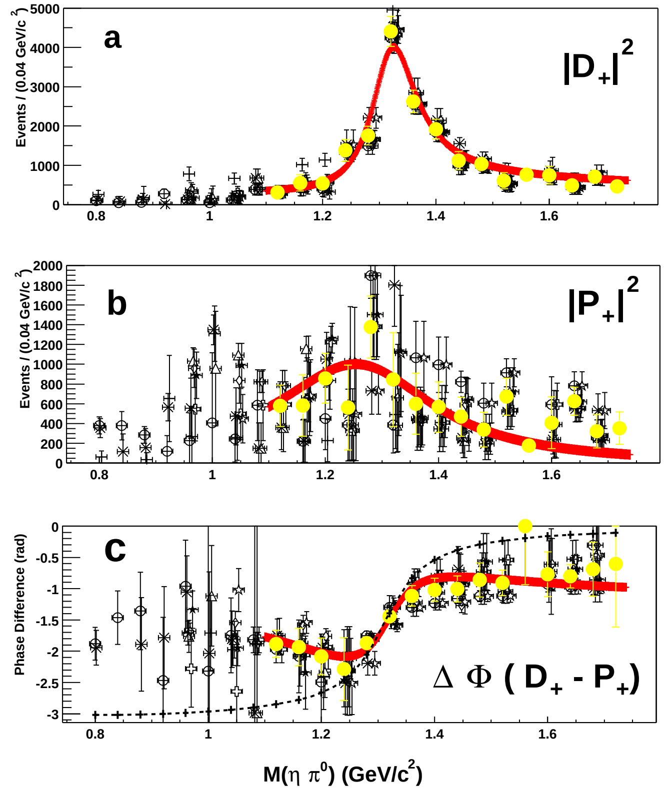

FIG. 2: The points shown are the various ambiguous solutions of PWA results. a)D_+ wave intensity, b)P_+ wave intensity and c)relative phase of P_+ and D_+ waves. MDF results (red lines) from fitting with fixed $a_2(1320)$ parameters and fitted π_1 parameters $M = 1257 \pm 25$ MeV/c^2 , $\Gamma = 354 \pm 58$ MeV/c^2. The averages of the ambiguous PWA solutions are yellow points. The dotted line in (c) is the D_+ phase if there is no P_+ phase variation.

The PWA results in each mass bin are shown in Fig. 2 as a point for every ambiguous solution..

MASS DEPENDENT FIT

To find resonant structure in the partial waves, we carried out a Mass-Dependent Fit (MDF) in the NPW sector. The PWA results in each mass bin were averaged between ambiguous solutions [12]. The mass dependence of the average values of the P_+ and D_+ intensities as well as their relative phase difference were then fit 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: six from two BW functions, one for the production phase (assumed constant) and two parameterizing the smooth background for the D_+ wave, as done in [12]. Fit is in the mass region $1.1 - 1.74$ GeV/c^2. The resonant hypothesis for D_+ and P_+ waves with a mass-independent production phase gives a χ^2/DoF=1.14.

The non-resonant hypothesis (no phase variation for the P_+ wave) gives χ^2/DoF=3.02. It is clear from Fig. 2c that a single resonant phase for the $a_2(1320)$ (dotted line) with a constant (non-resonant) P_+ wave is not satisfactory.

The π_1^0 resonant parameters for the fit with the average solutions and the average error matrix [12] are: $M = 1265 \pm 20$ MeV/c^2 and $\Gamma = 411 \pm 64$ MeV/c^2. These statistic errors are larger then for any separate combination of solutions. We consider them as a top estimation of statistical errors.

In order to obtain the systematic error range a large number ($\simeq 10^3$) of randomly chosen combinations of ambiguous solutions in each mass bin were used as input to the mass-dependent fit. The obtained distributions of mass and width of π_1^0 resonance were fitted by Gaussian. The mean values and RMS of these distributions give us the range of π_1^0 resonance parameters: $M = 1257 \pm 25 MeV/c^2$ and $\Gamma = 354 \pm 58 MeV/c^2$, the corresponding curves are shown in Fig. 2. The parameters obtained using the average solutions are inside this range. Note that the physical solution does not exactly coincide with the average solution nor with the mean values over the distributions. We can't determine it exactly in our analysis. We can extract from the data the ranges of the resonant parameters of π_1^0 inside the statistic and systematic error bars. these parameters are: $M = 1257 \pm 20 \pm 25$ MeV/c^2 and $\Gamma = 354 \pm 64 \pm 58$ MeV/c^2, where the first is statistic and the second systematic errors.

We have carried out an other independent analysis (so-called Mass-Dependent Partial Wave Analysis (MD-PWA) [12]) in an attempt to determine the robustness of our results. 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. This analysis is free from the problem of ambiguous solutions and thus it is not necessary to take an average of ambiguous solutions. But it is necessary to parameterize the mass dependence of every UNP wave and all relative phases, which are not known. We use the same parametrization of D_+ and P_+ waves as in MDF. The mass dependence of UNP waves were the polynomial of second order and constant phase except S_0 wave with BW form at $a_0(980)$ resonance parameters. The MD-PWA results for π_1 are $M = 1256 \pm 10$ MeV/c^2 and $\Gamma = 319 \pm 34$ MeV/c^2. These result is consistent with our MDF result.

In [12] was shown that a pure D_+ wave can introduce a P_+ wave artificially due to acceptance effects, resolutions. This "leakage" leads to a P_+ wave that mimics the D_+ intensity. In our case it has therefore the shape of $a_2(1320)$. The phase differences doesn't depend of mass. These features of "leakage from D_+ wave" allowed us to introduce in the fit a member describing leakage as the "intensity of leakage" multiplied on the form of mass dependence of D_+ wave with known $a_2(1320)$ resonance parameters. Our study of the leakage contribution to the P_+ wave from the D_+ wave shows that it is negligible.

CONCLUSIONS

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. Mass dependent fit of D_+ and $P+$ waves ant their relative phase allow to obtaine π_1^0 resonance parameters inside the range determined by statistical and systematic errors: $M = 1257 \pm 20 \pm 25$ MeV/c^2 and $\Gamma = 354 \pm 64 \pm 58$ MeV/c^2.

Evidence in favor of a resonance interpretation for the P_+ wave is the behavior of the $P_+ - D_+$ relative phase (Fig.2c), which can't explain by only $a_2(1320)$ resonance contribution. 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, as reported in Ref. [12].

The mass of the neutral exotic 1^{-+} state, decaying into $\eta\pi^0$, observed here: $M = 1257$ MeV/c^2 is lower than the mass observed in the Crystal Barrel experiment (1360 MeV) by about 100 MeV although the results are consistent within errors. The lower mass found here may be a consequence of interference between the resonant state and background in the $\eta\pi^0$ system, some of which may be from 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. There are also hypothesis that two or more the resonant 1^{-+} states may be present in $\eta\pi^0$ decay channel in interval mass of 1200 - 1400 MeV.

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