Exotic $\eta\pi$ State in $\bar{p}d$ Annihilation at Rest into $\pi^-\pi^0\eta$ $\mathbf{p}_{spectator}$

Crystal Barrel Collaboration

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With antiprotons stopped in liquid deuterium, the $\bar{p}n$ annihilation channel $\pi^-\pi^0\eta$ was studied using a final sample of 52 576 events obtained for a spectator proton momentum < 100 MeV/c. In the intensity distribution the $\eta\pi$ P-wave is clearly apparent by its interferences with the dominant $\rho^-(770)$ and $a_2(1320)$ two-meson resonances. A partial wave analysis of the data yields evidence for resonant behaviour of the $\eta\pi$ P-wave, which has the non-$q\bar{q}$ quantum numbers $I^G = 1^-$, $J^{PC} = 1^{-+}$. The extracted Breit-Wigner resonance parameters are m = (1400 ± 20 ± 20) MeV/c^2 and $\Gamma = (310 \pm 50^{+50}_{-30})$ MeV/c^2.

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Indications of non-$q\bar{q}$ structure are ubiquitous in meson spectroscopy [1,2]. Mixing with ordinary $q\bar{q}$ states seems to create a challenging diversity of mesonic resonances, but also delays unique identifications of the exotic structure until the spectroscopy for a given set of quantum numbers is rather complete. As a less complex manifestation, resonances with exotic quantum numbers are expected, which are forbidden for $q\bar{q}$ by symmetry principles. A prominent candidate is the "$\hat{\rho}$ " resonance with quantum numbers $I^G = 1^-$, $J^{PC} = 1^{-+}$ appearing as an intermediate $\eta\pi$ state at 1405 MeV/c^2 with a width of 180 MeV/c^2 in the GAMS study of the reaction $\pi^- p \to \pi^0 \eta n$ [3]. In the framework of quantum chromodynamics, the simplest configuration with these quantum numbers is a hybrid with a constituent gluon ($q\bar{q}g$), but also diquonia ($2q2\bar{q}$) and mesonic molecules have been considered in the theoretical discussion of this possible resonance [2,4].

In subsequent similar experiments, resonant behaviour of the $\eta\pi$ P-wave was also found [5,6], in contrast to an earlier study [7]. It is noted that, due to conservation laws, the P-wave in the $\eta\pi$ system carries, in any case, the exotic quantum numbers $I^G = 1^-$, $J^{PC} = 1^{-+}$. The neglect of some ambiguities in the GAMS analysis has been criticized [8]. Comparison of Refs. [3,5,6] does not yield consistent resonance characteristics. The VES results on $\eta\pi$ and $\eta^{'}\pi$ [5] show resonance structure of larger width as compared to GAMS, and point to an extension to additional resonance activity at higher mass. A recent high-statistics study at Brookhaven [9] finds good agreement with the VES results on $\eta\pi$ and reports a resonance width of almost 400 MeV/c^2. In all these cases, the evidence for an exotic $\eta\pi$ resonance is based exclusively on its interference with the prevailing a_2 resonance.

Here we report evidence for a resonant $\eta\pi$ P-wave produced in $\bar{p}n$ annihilation. The annihilation channel $\bar{p}n \to \pi^-\pi^0\eta$, studied here for the first time, is particularly sensitive to the $\eta\pi$ P-wave because only a very few intermediate states are allowed by selection rules. Isospin $I = 0$ two-meson resonances and in the case of $\bar{p}n$ S-wave annihilation also $J^P = 0^+$ resonances are excluded. This selectivity leads to a simple structure of the intensity distribution with dominant $\rho^-(770)$ and $\mathrm{a}_2^{0/-}(1320)$ bands upon which the $\eta\pi$ P-wave becomes visible by interference. A short account of this work is given in Ref. [10], details in Refs. [11,12].

In our previous study of $\bar{p}p$ annihilation into $\pi^0\pi^0\eta$ a weak but significant $\eta\pi$ P-wave contribution was found, but no resonance characteristics could be established [13]. A refined analysis including new data for annihilation in gas [14] favours resonant behaviour of the $\eta\pi$ P-wave. Due to isospin and G-parity selection rules, the annihilation reactions (a) $\bar{p}n \to \pi^-\pi^0\eta$ and (b) $\bar{p}p \to \pi^0\pi^0\eta$ occur from different initial states: (a) ${}^3S_1$ or ${}^1P_1$, (b) ${}^1S_0$, ${}^3P_1$ or ${}^3P_2$.

The data were collected with the Crystal Barrel detector [15] at CERN. Antiprotons with a momentum of 200 MeV/c from the Low Energy Antiproton Ring (LEAR) were stopped in a liquid deuterium target at the center of the detector. The beam, with an intensity of about 10^4 $\bar{p}/s$, was defined by means of a silicon counter telescope in front of the target. A one-prong trigger was derived from the outer of two proportional chambers that surround the target and from a cylindrical jet drift chamber that covers a solid angle of 0.93 x 4π sr. The enrichment of 1-prong events with respect to all annihilations in deuterium is estimated to amount to a factor of 14. Exposed to a magnetic field of 1.5 T parallel to the beam axis, the 23-layer drift chamber measures charged particle momenta. For a typical π^- momentum of 500 MeV/c a relative resolution (σ) of 2% is achieved. The two photon pairs from π^0 and η electromagnetic decays are detected by a barrel of 1380 CsI (Tl) crystals surrounding the drift chamber. This electromagnetic calorimeter covers a usable solid angle of 0.95 x 4π sr and provides polar and azimuthal angular resolutions of about 20 msr and an energy resolution $\sigma/E \approx 2.5\%/\sqrt[4]{E[GeV]}$.

Of the recorded sample of 8.1 million one-prong events a total of 590000 pass a preselection with the following requirements:

(i) Exactly one long negative charged track with hits in at least 15 layers of the drift chamber,

(ii) exactly four separable energy deposits of at least 13 MeV in the calorimeter that do not match the charged-particle trajectory, that are not centered in a crystal adjoining the beam pipe and that are not identified by "split-off" recognition routines [16] as secondaries produced in the detector by charged pions or photons,

(iii) a "missing mass" $\sqrt{(m_{\bar{p}d} - E_{tot})^2 - \mathbf{P}_{tot}^2}$ consistent with the mass of the undetected proton (within $\pm$ 230 MeV/c^2),

(iv) the appropriate kinematics as defined by a broad window in the P_{tot}/E_{tot} plane.

With respect to the requirements (i) and (iii) it is noted that all protons with momentum less than 200 MeV/c remain undetected since their range is smaller than our target radius and wall thickness.

All events that passed the preselection were kinematically fitted in two steps, first to the $\bar{p}d \to \pi^- 4\gamma\ p_{spectator}$ hypothesis (1 C fit) and secondly to the $\bar{p}d \to \pi^-\pi^0(\to \gamma\gamma)\eta(\to \gamma\gamma)\ p_{spectator}$ hypothesis (3 C fit). In the second step a confidence level CL$>$ 5% was required and events for which the second best $\pi^0(\to \gamma\gamma)\eta(\to \gamma\gamma)$ combination yielded a CL$>$ 3% were rejected. Two cuts were applied for background discrimination: CL($\bar{p}d \to \pi^-\pi^0\pi^0\ p_{spectator}$) $<$ 5% and CL($\bar{p}d \to \pi^-\eta\eta\ p_{spectator}$) $<$ CL($\bar{p}d \to \pi^-\pi^0\eta\ p_{spectator}$), in which way the sample was reduced by 2%. Finally, the proton momentum was limited to 100 MeV/c which yielded a sample of 52 576 events for the present analysis. This cut was chosen to permit the treatment of the proton as a spectator [17]. To check this assumption, various alternative momentum cuts were also applied.

As possible sources of background, several other channels of the type $\pi^- X$ $p_{spectator}$ (with X symbolising a single neutral meson or a pair of them) and the channel $\pi^-\pi^+\pi^0$ $n_{spectator}$ were studied by means of Monte Carlo simulations, based on the program package GEANT, using an empirical spectator momentum distribution fitted to data for the annihilation reaction $\bar{p}d \to \pi^0\pi^0\eta n_{spectator}$. Weighted by experimental branching ratios, the contributions to our final sample due to misidentified events from these channels are found to sum up to a total background of 0.5% with no significant structure in our phase space. This degree of purity is confirmed by the observation of 0.4% background below the π^0 peak in the experimental $\gamma\gamma$ invariant mass spectrum when the hypothesis $\pi^-\pi^0\eta$ $p_{spectator}$ is replaced by $\pi^-\gamma\gamma\eta$ $p_{spectator}$ in the event reconstruction.

The acceptance of the apparatus and of all selection and reconstruction steps was determined by high statistics Monte Carlo simulations. For phase-space distributed $\pi^-\pi^0\eta(\to \gamma\gamma)$ $p_{spectator}$ events, the overall acceptance amounts to 12.9% for the 100 MeV/c spectator momentum cut. The distribution of the acceptance over phase space is rather flat, except for smooth modulations close to the kinematic boundary. The corresponding acceptance weighting factors are taken into account in the analysis below.

By normalizing the total yield to the branching ratio for all $\bar{p}n \to 1$ prong channels [18,19] we find

BR$(\bar{p}n \to \pi^-\pi^0\eta) = (14.1 \pm 1.5) \times 10^{-3}$.

This value applies to the present momentum cut, but is not expected to differ significantly from the unrestricted BR (see Ref. [19]).

The Dalitz plot (DP) of the intensity distribution in the present three-body annihilation channel of $\bar{p}n$ is in principle a superposition of DPs with slightly different phase space boundaries corresponding to different values of the spectator momentum. However, for values below 100 MeV/c the Monte Carlo simulations show that this effect and the associated broadening of structures in the intensity distribution is negligibly small.

All reconstructed 52 576 events are presented in the DP and its projections in Figs. 1 and 2, respectively. The DP is characterized by a simple pattern with a prominent diagonal $\rho^-(770)$ band and two weaker orthogonal bands in the region of the $a_2(1320)$. The latter show large modulations typical of interference effects.

The experimental intensity distribution is analysed using the partial wave method. Following the usual "isobar model" approach, we assume that the

$\bar{p}n$ system decays via intermediate two-body states into the final three-body $\pi^-\pi^0\eta$ state, i.e. via $\pi^-\pi^0$ resonances with a recoiling η or $\pi\eta$ resonances with a recoiling π. Using the Zemach formalism [20], the transition amplitude A_j for a given intermediate state j is factorized into a spin-parity function that describes the dependence on the relative momentum vectors of production and decay of an intermediate resonance, a barrier penetration factor for production [21] and a relativistic Breit-Wigner amplitude that parametrizes the resonance. In this parametrization, the width Γ is multiplied with a phase space and barrier penetration factor, yielding a mass-dependent width $\Gamma(m)$. Explicit formulae are given in [13,22]. These amplitudes are multiplied by complex coefficients $\alpha_j = a_j \cdot exp(i\phi_j)$ and added coherently. The theoretical intensity is the incoherent sum of intensities from the $\bar{p}n$ initial states $^3S_1$ and $^1P_1$.

The real coefficients a_j and φ_j are fitted by minimizing

$$\chi^2 = \sum \frac{(N_i^{exp} \cdot c_i - N_i^{theor})^2}{\sigma_i^2}, \qquad (1)$$

where the sum extends over all DP cells i and c_i designates the acceptance weighting factors for these cells. The errors of the latter and of N_i^{theor} are negligibly small compared to the statistical errors σ_i. A cell area of (7.75 x 10^4 MeV$^2/c^4)^2$ is chosen. The fit results turn out to be insensitive to moderate variations of the cell size. Cells are not taken into account if they extend beyond the phase space boundary or if the content is less than 10 events. In this way a number of 411 cells, containing 50 644 events, are used for fitting.

The model space is strongly restricted by selection rules (see e.g. [23]). Of all known (or presumed) resonances [13,24], with nominal mass inside or close to our phase space boundary, only $\rho^-(770)$ and $\rho^-(1450)$ can appear as intermediate $\pi^-\pi^0$ resonances and only $a_2(1320)$ and $a_2(1650)$ as intermediate $\eta\pi$ resonances for the $^3S_1$ initial state. In addition, the $\eta\pi$ resonances $a_0(980)$ and $a_0(1450)$ are allowed if the $\bar{p}n$ annihilation occurs from the $^1P_1$ state. Contributions from an exotic $\eta\pi$ P-wave resonance are possible for both initial states.

Our final fit, yielding $\chi^2/N_{d.o.f.}$ = 506/(411-20) = 1.29, is compared to the data in Fig. 3a and the results for the different intermediate states, which are discussed below, are listed in Table 1. Their individual rates were obtained by integrating the squared magnitudes of the annihilation amplitudes A_j over the available phase space and by dividing these by the total intensity of the fit. Because of mutual interferences they do not add up to 100%.

The masses and widths of $\rho^-(770)$ and $a_2(1320)$ were treated as free parameters in this fit, yielding a ρ^- mass 8 MeV/c^2 above the PDG average [24] but otherwise agreement with the PDG values if the widths [24] are folded with our experimental resolution $\sigma \leq 20$ MeV/c^2. Fixing these resonance parameters to the PDG values, the fit quality gets slightly worse ($\chi^2/N_{d.o.f.} = 1.42$) with no significant changes in the results.

The structureless χ_i^2 distributions in Fig. 3a, with merely statistical fluctuations, show that the model space of Table 1 is sufficient to account for the data. Introducing in addition the $a_0(980)\pi$ and $a_0(1450)\pi$ intermediate states, accessible from the $^1P_1$ initial state, does not change the fit quality and attributes vanishingly small rates to them. The absence of sharp bands from the narrow $a_0^{0/-}(980)$ resonance is already evident in the DP (Fig. 1). Also contributions from $\rho^-(1450)\pi^0$ and $a_2(1650)\pi$ were found to be negligible.

The inclusion of the initial $\bar{p}n$ $^1P_1$ state is essential for the fit quality. Without this initial state, $\chi^2/N_{d.o.f.}$ increases to values above 3, even if all accessible intermediate states are included; also characteristic structures in the distribution of χ_i^2 over phase space show the need for this initial state. By varying the spectator momentum cut, we could qualitatively verify the increase of the $^1P_1/^3S_1$ ratio with increasing spectator momentum, expected for annihilation reactions on deuterium [25].

The $\eta\pi$ P-wave contributes a considerable fraction of the total rate, summing up to 11% (Table 1). Its intensity accumulates in a broad range around the centre of the DP. However, it is mainly the interference with the other intermediate states that makes the intensity distribution specifically sensitive to the $\eta\pi$ P-wave and its resonance characteristics. The interference signatures become evident when fits that do not include the $\eta\pi$ P-wave are compared with the data. Fig. 3b shows the distribution of deviations χ_i^2 for the best fit including only the $\rho^-(770)$ and $a_2(1320)$ and in addition the $a_0(980)$ and $a_0(1450)$ contributions from the $^3S_1$ and $^1P_1$ initial states, where already the total $\chi^2/N_{d.o.f.} = 1223/(411\text{-}12) = 3.07$ indicates the deficiency of the model. Structures are visible in this representation that are characteristic of the interference of amplitudes for an $(\eta\pi)_P$ resonance with amplitudes for the ρ^- and a_2 resonances. By comparison with Fig. 4, which shows the calculated intensity patterns for these interferences, the islands of missing experimental intensity (left panel of Fig. 3b) around $m^2(\eta\pi) \approx 1$ and (1.5-2) GeV$^2/c^4$ are assigned to destructive interference of the $\eta\pi$ P-wave with the $a_2(1320)$ and the islands positioned above the $\rho^-(770)$ band are assigned to destructive interference of the $\eta\pi$ P-wave with the $\rho^-(770)$. The former ones are also recognized in the original DP (Fig. 1). The islands of surplus experimental intensity (right panel of Fig. 3b) positioned above and below the ρ^- band are identified as regions of the corresponding constructive interferences. These enhancements are also recognized in Fig. 1. Since the intensity distributions for fixed $m^2(\eta\pi)$ reflect the angular distribution of the secondary decay with respect to the primary recoil momentum, the observed change from positive to negative deviation at the a_2 mass and above gives evidence of a forward/backward asymmetry and, hence, of the coherent addition of an odd-ℓ partial wave to the $\eta\pi$ D-wave.

The fit model without the $\eta\pi$ P-wave was modified by treating the ρ^- and a_2 resonance parameters as freely adjustable. The resulting $\chi^2/N_{d.o.f.} = 1063/(411\text{-}16) = 2.69$ is still unacceptably large and too large values are found for the a_2 mass and, in particular, its width (50% above the PDG value), which indicates compensation for the missing contribution. Treatment of the parameters of both a_0 resonances (see above) as freely adjustable and inclusion of the quoted ρ^- and a_2 resonance candidates at higher mass does not lead to a significantly better description of the data.

The observed interference with the ρ^- and a_2 bands yields evidence not only for the presence of the $\eta\pi$ P-wave but also for its resonant character. The phase motion of the $\eta\pi$ P-wave is probed in different regions of the DP by its overlap with both the ρ^- and the a_2 bands which have a relative phase well determined by their crossing. For example, between the interference minima with these two bands, discussed above, the phase of the fitted P-wave amplitude rotates by about 80^o. This feature distinguishes the present study of a 3 body annihilation channel from those of π induced production where only the interference with the a_2-resonance is accessible [3,5-9]. Fig. 5 shows the intensity distribution of the fitted $(\eta\pi)_P\pi$ amplitudes and of their interferences with the other amplitudes for both initial $\bar{p}n$ states, as given in Table 1. Constructive and destructive interference is evident on opposite sides, respectively, of the $\rho^-(770)$ band position (cf. Fig. 1). Along a parallel to the ρ^--band, the growth and fall of the constructive term reflects the almost complete phase rotation of the $(\eta\pi)_P$ resonance.

We have simulated a nonresonant $\eta\pi$ P-wave in the framework of the present model by increasing the Breit-Wigner resonance width. For $\Gamma = 1$ GeV/c^2, the fit gets significantly worse ($\Delta\chi^2 = 114$, with structures in the distribution of χ_i^2) and it demands very large relative intensities for the initial $^1P_1$ state exceeding the $^3S_1$ intensity for the $\rho^-\eta$ intermediate state by a factor of 5 and summing up to 60%, which would be hard to accept with the present knowledge of annihilation dynamics. As an alternative check of the uniqueness of the resonant solution for the $\eta\pi$ P-wave we have substituted an effective range production amplitude [26] into the fit. Using scattering parameters a = (- scattering length)$^{-1}$ and b = 2 $\times$ (effective range) as defined in Ref. [26], the fits diverge for $a < 0$, $b < 0$, characterizing nonresonant solutions. However, convergence occurs at scattering parameters $a > 0$, $b < 0$ yielding an effective range amplitude in complete agreement with the Breit-Wigner amplitude of our resonance fit.

To investigate a possible threshold effect of the $f_1\pi$ channel which opens at a mass of 1420 MeV/c^2, we have applied Flatté's resonance parametrization [22,27], where the width $\Gamma(m)$ in the Breit-Wigner denominator is replaced by $\Gamma_{\eta\pi}(m) + 2(q_{f_1\pi}/m)\Gamma_{f_1\pi}$. For the particular case of a large width $\Gamma_{\eta\pi} = 1$ GeV/c^2, the fit yields $\Gamma_{f_1\pi} = 1.8$ GeV/c^2, and a slightly worse description of the data ($\Delta\chi^2 = 42$) as compared to the best fit (Table 1) with indications of nonstatistical deviations in the χ_i^2 distribution. In this case, structure of smaller width is ascribed to a cusp generated by the threshold channel [27]. This fit was constrained by the assumption of a vanishing $(\eta\pi)_P\pi$,$L = 2$ amplitude (cf. Table 1). Without this constraint, initial state intensity ratios, I($^1P_1$):I($^3S_1$), emerge that are hard to accept, e.g. 2:1 for the $\rho^-(770)\pi$ contributions. Further investigation of the threshold effect will require a proper coupled channel treatment, which may also include molecular resonance formation [22]. The corresponding $f_1\pi$ rate should be determined experimentally.

The sensitivity of the fit using the simple Breit-Wigner parametrization to the $(\eta\pi)_P$ width is probed by a χ^2 scan (Fig. 6). This scan is obtained from fits for different fixed values of Γ, using the model space of Table 1 except for the insignificant $(\eta\pi)_P\pi$, $L = 2$ contribution. A well defined minimum is observed, and values of Γ below 200 MeV/c^2 or above 500 MeV/c^2 appear to account insufficiently for the data. To assess the systematic errors, we have examined the dependence of the resonance parameters on the following modifications to the fit model:

1) inclusion of the resonances [24] $a_0(980)$, $a_0(1450)$, $\rho^-(1450)$ and of the resonance candidate [13] $a_2(1650)$, 2) omission of the $^1P_1$, $L = 2$ amplitude of the $(\eta\pi)_P\pi$ intermediate state (see Table 1), 3) omission of the $^1P_1$ initial state, 4) variation of the a_2 line shape due to the effect of the $\rho\pi$ decay mode on the mass-dependent width (see Ref. [28]), 5) variation of the radius parameter in the resonance-decay barrier penetration factor [22] between 0.6 and 1.4 fm, 6) variation of the spectator momentum cut between 80 and 160 MeV/c^2. The resulting variations of the resonance parameters are smaller or of the same size (modification 6) as the statistical uncertainty. Concerning possible effects of final state interactions (fsi) with the "spectator" proton, the π^-/π^0 exchange symmetry and the dependence of the intensity distribution on the spectator momentum provide sensitive checks. The experimental intensity distribution (Fig. 1) is consistent with π^-/π^0 symmetry, taking the small acceptance corrections into account. Because of different isospin coupling with the proton, fsi would produce an asymmetry, as can be verified, e.g. for the case of $\bar{p}d \to \Delta\pi\eta$. For different slices of the spectator momentum distribution between 0 and 160 MeV/c, the only significant change of the partial wave decomposition occurs in the $^3S_1/^1P_1$ intensity ratio as noted above. Contributions from fsi are expected [17] to show an order of magnitude increase with increasing proton momentum in this range, as we have verified by a Monte Carlo simulation for the $\Delta^-\pi^0\eta$ channel.

In conclusion, we arrive at the following resonance parameters for the exotic

$\eta\pi$ P-wave :

$m = (1400 \pm 20_{stat} \pm 20_{syst})$ MeV/c^2,

$\Gamma = (310 \pm 50_{stat} + 50/-30_{syst})$ MeV/c^2.

The statistical errors are derived from a MINOS analysis [29], the systematic errors reflect the variations resulting from the above modifications 1)-6). These resonance parameters are consistent with studies [5,9] of pion induced peripheral reactions. More complex multiple resonance structure extending to higher $\eta\pi$ mass outside the present phase space cannot be excluded, of course, from our work, and may be required to reconcile all quoted studies. Our resonance parameters are extracted under the model assumption of a single Breit-Wigner resonance, which yields a quite satisfactory description of the data. The relative rate of the exotic resonance is of a similar size as the a_2 rate and it exceeds by far the $(\eta\pi)_P$ rate in the annihilation $\bar{p}p \to \pi^0\pi^0\eta$ where it is produced from a different atomic state, as outlined in the beginning. It is conceivable that the different angular momentum configuration causes a different dynamical selectivity in the intermediate state. The relatively large production rate and the superposition with two different intermediate states have made possible the present observation of resonant behaviour of the $\eta\pi$ P-wave.

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Table 1

Results of the partial wave analysis yielding $\chi^2/N_{d.o.f.}$ = 506/(411-20) = 1.29 and Breit-Wigner parameters m = (1398 ± 20), Γ = (309 ± 50) MeV/c^2 for the $(\eta\pi)_P^{0/-}$ resonance. The rates given for the two incoherent initial states (uncertain within ± 3%) include all interferences of the individual intermediate states, and hence differ from the sums of the individual rates (see text). For the $a_2\pi$ and $(\eta\pi)_P\pi$ intermediate states the tabulated rates refer to the coherent sum of both charge combinations.

Initial state	Intermediate state	Rate (%)	ϕ_j (^{0})
^{3}S$_1$ (66.4%)			
	$\rho^-(770)\eta$	30.0 ± 3.5	0 (fixed)
	$a_2(1320)\pi$	11.1 ± 1.0	7 ± 8
	$(\eta\pi)_P\pi$	7.9 ± 1.0	210 ± 10
^{1}P$_1$ (33.6%)			
	$\rho^-(770)\eta$ (L=0)	10.3 ± 3.0	0 (fixed)
	(L=2)	17.3 ± 1.2	145 ± 10
	$a_2(1320)\pi$	3.8 ± 0.8	315 ± 25
	$(\eta\pi)_P\pi$ (L=0)	2.8 ± 1.3	70 ± 35
	(L=2)	0.5 ± 0.5	110 ± 50