

THE 1.4 GEV $J^{PC} = 1^{-+}$ STATE AS AN INTERFERENCE OF A NON-RESONANT BACKGROUND AND A RESONANCE AT 1.6 GEV

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We investigate theoretical interpretations of the 1.4 GeV J^{PC} exotic resonance reported by the E852 collaboration. A K-matrix analysis shows that the 1.4 GeV enhancement in the E852 $\eta\pi$ data can be understood as an interference of a non-resonant Deck-type background and a resonance at 1.6 GeV.

^a Evidence for a $J^{PC} = 1^{-+}$ isovector resonance $\hat{\rho}(1405)$ at 1.4 GeV in the reaction $\pi^- p \rightarrow \eta\pi^- p$ has been published recently by the E852 collaboration at BNL¹. The mass and width quoted are $1370 \pm 16_{-30}^{+50}$ MeV and $385 \pm 40_{-105}^{+65}$ respectively. These conclusions are strengthened by the claim of the Crystal Barrel collaboration that there is evidence for the same resonance in $p\bar{p}$ annihilation with a mass of $1400 \pm 20 \pm 20$ MeV and a width of $310 \pm 50_{-30}^{+50}$ MeV², consistent with E852. However, the Crystal Barrel state is not seen as a peak in the $\eta\pi$ mass distribution, but is deduced from interference in the Dalitz plot. Since the J^{PC} of this state is “exotic”, i.e. it implies that it is *not* a conventional meson, considerable excitement has been generated, particularly because the properties of the state appear to be in conflict with theoretical expectations.

In addition there are two independent indications of a more massive isovector $J^{PC} = 1^{-+}$ exotic resonance $\hat{\rho}(1600)$ in $\pi^- N \rightarrow \pi^+ \pi^- \pi^- N$. The E852 collaboration recently reported evidence for a resonance at $1593 \pm 8_{-47}^{+29}$ MeV with a width of $168 \pm 20_{-12}^{+150}$ MeV³. These parameters are consistent with the preliminary claim by the VES collaboration of a resonance at 1.62 ± 0.02 GeV with a width of 0.24 ± 0.05 GeV⁴. In both cases a partial wave analysis was performed, and the decay mode $\rho^0 \pi^-$ was observed. There is also evidence for $\hat{\rho}(1600)$ in $\eta' \pi$ peaking at 1.6 GeV⁵. It has been argued that the $\rho\pi$, $\eta' \pi$ and $\eta\pi$ couplings of this state qualitatively support the hypothesis that it is a hybrid meson, although other interpretations cannot be entirely eliminated⁶.

Recent flux-tube and other model estimates⁷ and

lattice gauge theory calculations⁸ for the lightest 1^{-+} hybrid support a mass substantially higher than 1.4 GeV and often above 1.6 GeV⁶. Further, on quite general grounds, it can be shown that an $\eta\pi$ decay of 1^{-+} hybrids is unlikely⁹. There is thus an apparent conflict between experimental observation and theoretical expectation as far as the 1.4 GeV peak is concerned.

The purpose of the present paper is to propose a resolution of this apparent conflict. We suggest a mechanism whereby an appropriate $\eta\pi$ decay of a hybrid meson can be generated and argue that there is only one $J^{PC} = 1^{-+}$ isovector exotic, the lower-mass signal in the E852 experiment being an artefact of the production dynamics. We demonstrate explicitly that it is possible to understand the 1.4 GeV peak observed in $\eta\pi$ as a consequence of a 1.6 GeV resonance interfering with a non-resonant Deck-type background with an appropriate relative phase. We do *not* propose that there should necessarily be a peak at 1.4 GeV; but that if experiment unambiguously confirms a peak at 1.4 GeV, it can be understood as a 1.6 GeV resonance interfering with a non-resonant background.

1 Interference with a non-resonant background

The current experimental data on the 1.6 GeV state is consistent with mass predictions and decay calculations for a hybrid meson^{6,10}. This then leaves open the interpretation of the structure at 1.4 GeV.

There are two basic problems to be solved. Firstly it is necessary to find a mechanism which can generate a suitable $\eta\pi$ width for the hybrid. Then having established that, it is necessary to provide a mechanism to produce a peak in the cross section which is some way below the real resonance position.

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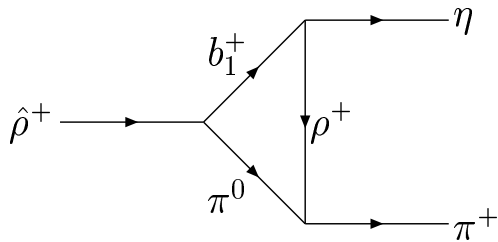


Figure 1: Decay of $\hat{\rho}$ to $\eta\pi$ via final state interactions.

The $\eta\pi$ peak in the E852 data spans the $\rho\pi$ and $b_1\pi$ thresholds, so we propose a Deck-type model¹¹ as a source of a non-resonant $\eta\pi$ background. We then show that, within the K-matrix formalism, interference between this background and a resonance at 1.6 GeV can account for the E852 $\eta\pi$ data.

1.1 $\eta\pi$ width of a 1.6 GeV state

Although the $\eta\pi$ width of a hybrid is suppressed by symmetrization selection rules⁹ which operate on the quark level and have been estimated in QCD sum rules to be tiny (~ 0.3 MeV)¹², long distance contributions to this width are possible.

An essential ingredient is the presence of an allowed dominant decay which can couple strongly to the channel of interest. In the flux-tube model $b_1\pi$ is such a dominant decay¹⁰, and it is strongly coupled to $\eta\pi$ by ρ exchange (see Figure 1). Diagrams like that in Fig. 1 are expected to make the $\eta\pi$ width more appreciable.

1.2 Non-resonant $\eta\pi$ Deck background

The 1.4 GeV peak in the $\eta\pi$ channel occurs in the vicinity of the $\rho\pi$ and $b_1\pi$ thresholds, and it is therefore natural to consider these as being responsible in some way for the $\eta\pi$ peak. The Deck mechanism¹¹ is known to produce broad low-mass enhancements for a particle pair in three-particle final states, for example in $\pi p \rightarrow (\rho\pi)p$. In this latter case, the incident pion dissociates into $\rho\pi$, either of which can then scatter off the proton¹³. At sufficiently high energy and presumed dominance of the exchange of vacuum quantum numbers (pomeron exchange) for this scattering one obtains the “natural parity change” sequence $\pi \rightarrow 0^-, 1^+, 2^- \dots$ (the Gribov-Morrison rule¹⁴). However if the scattering involves the exchange of other quantum numbers then additional spin-parity combinations can be obtained, including $J^P = 1^-$. This can be seen explicitly in ref.¹¹ for the reaction $\pi p \rightarrow (\rho\pi)p$ in which the full πp scattering amplitude was used, so that the effect of exchanges other than the pomeron are auto-

matically included. The J^P sequence from the “natural parity change” dominates due to the dominant contribution from pomeron exchange, but other spin-parity states are present at a non-negligible level. The Reggeised Deck effect can simulate resonances, both in terms of the mass distribution and the phase^{11,15}. It can produce circles in the Argand plot, the origin of which is the Regge phase factor $\exp[-i\frac{1}{2}\pi\alpha(t_R)]$.

It is also important to note that rescattering of the lighter particle from the dissociation of the incident beam particle is not a prerequisite, and indeed both can contribute¹³. We suggest that in our particular case the relevant processes are (from left to right in Figure 2)

1. $\pi \rightarrow b_1\omega$, $\omega p \rightarrow \pi p$ giving a $b_1\pi$ final state.
2. $\pi \rightarrow \pi\rho$, $\rho p \rightarrow \eta p$ giving a $\eta\pi$ final state.
3. $\pi \rightarrow \rho\pi$, $\pi p \rightarrow \pi p$ and $\rho p \rightarrow \rho p$ giving a $\pi\rho$ final state.

For each of these processes the rescattering will be predominantly via ρ (natural parity) exchange to give the required parity in the final state. Obviously process (ii) produces a final $\eta\pi$ state directly, but for (i) and (iii) the $b_1\pi$ and $\rho\pi$ final states are required to rescatter into $\eta\pi$.

The characteristic mass-dependence is a peak just above the threshold. Thus there are three peaks from our proposed mechanism: a sharp peak just above the $\eta\pi$ threshold; a broader one at about 1.2 GeV from the $\rho\pi$ channel; and a very broad one at about 1.4 GeV from the $b_1\pi$ channel. The first of these is effectively removed by experimental cuts, but the net effect of the two latter is to produce a broad peak in the $\eta\pi$ channel. Thus invoking this mechanism does provide an explanation of the larger width of the $\eta\pi$ peak at 1.4 GeV in the E852 data compared to that of the $\rho\pi$ peak at 1.6 GeV. Because of the resonance-like nature of Deck amplitudes it is also possible in principle to simulate the phase variation observed. However as there are Deck amplitudes and the 1.6 GeV resonance, presumably produced directly, it is necessary to allow for interference between them. We use the K-matrix formalism to calculate this, and also to demonstrate that the Deck mechanism is essential to produce the 1.4 GeV peak.

1.3 K-matrix with P-vector formalism

It is straightforward to demonstrate that within the K-matrix formalism it is impossible to understand the $\eta\pi$ peak at 1.4 GeV as due to a 1.6 GeV state if only resonant decays to $\eta\pi$, $\rho\pi$ and $b_1\pi$ are allowed despite the strong threshold effects in the two latter channels^b. We find

^bThe use of $b_1\pi$ is not critical here: any channel with a threshold near 1.4 GeV will suffice.

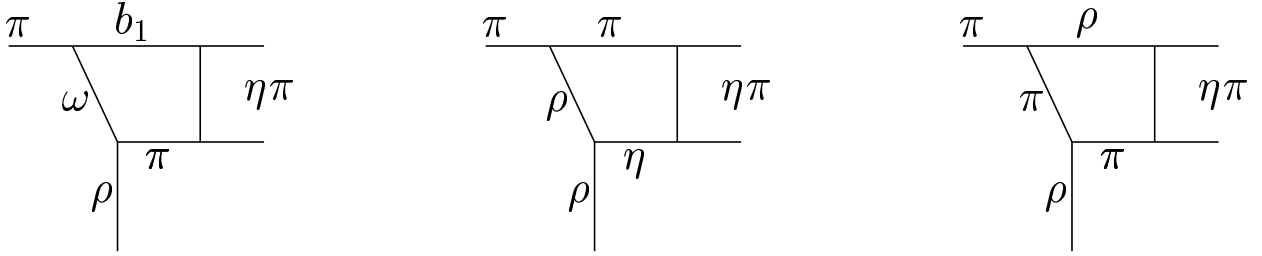


Figure 2: Deck background production in $\eta\pi$.

that for a $b_1\pi$ width of ≈ 200 MeV and $\eta\pi$ and $\rho\pi$ widths in the region $1 - 200$ MeV there is no shift of the peak. However, when a non-resonant $\eta\pi$ P-wave is introduced, the interference between this and the 1.6 GeV state can appear as a 1.4 GeV peak in $\eta\pi$.

We have seen that the non-resonant $\eta\pi$ wave can have significant presence at the $b_1\pi$ or $f_1\pi$ threshold (called the “P+S” threshold), e.g. 1.368 GeV for $b_1\pi$, because of the substantial “width” generated by the Deck mechanism. Since the hybrid is believed to couple strongly to “P+S” states due to selection rules¹⁶, the interference effectively shifts the peak in $\eta\pi$ down from 1.6 GeV to 1.4 GeV. It is not necessary for the 1.6 GeV resonance to have a strong $\eta\pi$ decay. It is significant that the E852 experiment finds $\hat{\rho}$ at $1370 \pm 16_{-30}^{+50}$ MeV, near the $b_1\pi$ threshold, but not at 1.6 GeV. It is possible for a state to peak near the threshold of the channel to which it has a strong coupling, assuming that the (weak) channel in which it is observed has a significant non-resonant origin.

We follow the K-matrix formalism in the P-vector approach as outlined in^{17,18}. We assume there to be a $\hat{\rho}$ with $m_{\hat{\rho}} = 1.6$ GeV as motivated by the structure observed in $\rho\pi$ ³. The problem is simplified to the case where there is decay to two observed channels i.e $\eta\pi$ and $\rho\pi$, and one unobserved $P + S$ channel. These channels are denoted 1, 2 and 3 respectively. The production amplitudes and the amplitude after final-state interactions are grouped together in the 3-dimensional P- and F-vectors respectively. In order to preserve unitarity¹⁷ we assume a real and symmetric 3×3 K-matrix. The amplitudes after final-state interactions and production are related by¹⁷

$$F = (I - iK)^{-1}P \quad (1)$$

We define the widths as

$$\Gamma_i = \gamma_i^2 \Gamma_{\hat{\rho}} \frac{B^2(q_i)}{B^2(q_i^{\hat{\rho}})} \rho(q_i) \quad i = 1, 2 \quad (2)$$

$$\Gamma_3 = \gamma_3^2 \Gamma_{\hat{\rho}} \rho(q_3) \quad (3)$$

where q_i is the breakup momentum in channel i from a state of effective mass w , and $q_i^{\hat{\rho}}$ is the breakup momentum in channel i from a state of effective mass $m_{\hat{\rho}}$. The kinematics is taken care of by use of the phase space factor

$$\rho(q) = \frac{2q}{w} \quad (4)$$

and the P-wave angular momentum barrier factor

$$B^2(q) = \frac{(q/q_R)^2}{1 + (q/q_R)^2} \quad (5)$$

where the range of the interaction is $q_R = 1$ fm = 0.1973 GeV.

We assume the experimental width in $\rho\pi$ of $\Gamma_{\hat{\rho}} = 168$ MeV³ to be the total width of the state^c. We adopt the flux-tube model of Isgur and Paton and use the $\rho\pi$ and $b_1\pi$ widths which it predicts for a hybrid of mass 1.6 GeV. Since the model predicts that the branching ratio of a hybrid to $b_1\pi$ is 59 – 74 % and to $f_1\pi$ is 12 – 16 %¹⁰, we obtain the $P + S$ -wave width to be 120 – 150 MeV. Analysis of the data shows that the $\rho\pi$ branching ratio of $\hat{\rho}(1600)$ is 20 ± 2 %⁶, corresponding to a $\rho\pi$ width of 30 – 37 MeV. This is consistent with flux-tube model predictions of 9 – 22 %¹⁰. For the simulation we use a $b_1\pi$ width of 120 MeV, a $\rho\pi$ width of 34 MeV, and an $\eta\pi$ width of 14 MeV, well within the limits set by the doorway calculation. We neglect other predicted modes of decay since we restrict our analysis to three channels.

The K-matrix elements are

$$K_{ij} = \frac{m_{\hat{\rho}} \sqrt{\Gamma_i \Gamma_j}}{m_{\hat{\rho}}^2 - w^2} + c_{ij} \quad (6)$$

where c_{ij} includes the possibility of an unknown background.

In the simulation we assume that the Deck terms can be treated as conventional resonances. This is not

^cIt is found that our results in Fig. 3 are very similar even for a width of 250 MeV.

necessary, but is done to reduce the number of free parameters. We assume that the $\eta\pi$ Deck amplitude is produced predominantly via the $b_1\pi$ and $\rho\pi$ channels, and so is modelled as a resonance at a mass $m_{b1} = 1.32$ GeV and a width $\Gamma_{b1} = 300$ MeV. This width fits the E852 data at low $\eta\pi$ invariant masses (see Figure 3a). The $\rho\pi$ background is assumed to peak at a mass $m_{b2} = 1.23$ GeV with a width $\Gamma_{b2} = 400$ MeV, which when plotted as an invariant mass distribution effectively peaks at ~ 1.15 GeV, in agreement with detailed Deck calculations in the 1^{++} wave¹¹.

We incorporate the $\eta\pi$ and $\rho\pi$ Deck background by putting $c_{ij} = 0$ except for

$$c_{11} = \frac{m_{b1}\Gamma_{b1}}{m_{b1}^2 - w^2} \quad c_{22} = \frac{m_{b2}\Gamma_{b2}}{m_{b2}^2 - w^2} \quad (7)$$

The widths are defined analogously to Eq. 2 as

$$\Gamma_{bi} = \gamma_{bi}^2 \Gamma_{\hat{\rho}} \frac{B^2(q_i)}{B^2(q_i^b)} \rho(q_i) \quad i = 1, 2 \quad (8)$$

where q_i^b is the breakup momentum from a state of effective mass m_{bi} (for $i = 1, 2$).

The production amplitudes are given by

$$P_i = \frac{m_{\hat{\rho}} V_{\hat{\rho}} \sqrt{\Gamma_i \Gamma_{\hat{\rho}}}}{m_{\hat{\rho}}^2 - w^2} + c_i \quad (9)$$

where the (dimensionless) complex number $V_{\hat{\rho}}$ measures the strength of the production of $\hat{\rho}$. We take $c_3 = 0$ and

$$c_1 = \frac{m_{b1} V_{b1} \sqrt{\Gamma_{b1} \Gamma_{\hat{\rho}}}}{m_{b1}^2 - w^2} \quad c_2 = \frac{m_{b2} V_{b2} \sqrt{\Gamma_{b2} \Gamma_{\hat{\rho}}}}{m_{b2}^2 - w^2} \quad (10)$$

where the complex numbers V_{bi} gives the production strengths of the Deck background in channel i .

The results of this fit are shown in Fig. 3 and clearly provide a good description of the $\eta\pi$ data^{1,18}.

We briefly discuss the results. Fig. 3a indicates a steep rise for low invariant $\eta\pi$ masses, and a slow fall for large $\eta\pi$ masses. This naturally occurs because of the presence of the resonance at 1.6 GeV in the high mass region, which shows as a shoulder in our fit. Figure 3b reproduces the experimental slope and phase change in $\eta\pi$ ¹⁸. One might find this unsurprising, since the background changes phase like a resonance. However, we have confirmed, by assuming a background that has constant phase as a function of $\eta\pi$ invariant mass, that the experimental phase shift is still reproduced. The experimental phase shift is hence induced by the resonance at 1.6 GeV.

Without the inclusion of a dominant $P + S$ -wave channel the $\eta\pi$ event shape clearly shows two peaks, one at 1.3 GeV and one at 1.6 GeV, which is not consistent

with the data¹. The phase motion is also more pronounced in the region between the two peaks than that suggested by the data¹⁸. The rôle of the dominant $P + S$ -channel is thus that at invariant masses between the two peaks, the formalism allows coupling of the strong $P + S$ channel to $\eta\pi$, so that the $\eta\pi$ appears stronger than it would otherwise, interpolating between the peaks at 1.3 and 1.6 GeV, consistent with the data¹. A dominant $P + S$ decay of the $\hat{\rho}$ is hence suggested by the data.

2 Discussion

We have argued that on the basis of our current understanding of meson masses it is implausible to interpret the 1.4 GeV peak seen in the $J^{PC} = 1^{-+}$ $\eta\pi$ channel by the BNL E852 experiment as evidence for an exotic resonance at that mass. We acknowledge that this is not a proof of non-existence and note the Crystal Barrel claim for the presence of a similar state at $1400 \pm 20 \pm 20$ MeV in the reaction $p\bar{p} \rightarrow \eta\pi^+\pi^-$. However this is not seen as a peak and is inferred from the interference pattern on the Dalitz plot. It has not been observed in other channels in $p\bar{p}$ annihilation at this mass, which is required for confirmation. So at present we believe that the balance of probability is that the structure does not reflect a real resonance.

Given this view, it is then necessary to explain the data and in particular the clear peak and phase variation seen by the E852 experiment. Additionally the observation of the peak only in the $\eta\pi$ channel, which is severely suppressed by symmetrization selection rules, requires justification. We have dealt with these two questions in reverse order. We first suggest final-state interactions can generate a sizable $\eta\pi$ decay. We then suggest that the E852 $\eta\pi$ peak is due to the interference of a Deck-type background with a hybrid resonance of higher mass, for which the $\hat{\rho}$ at 1.6 GeV is an obvious candidate. This mechanism also provides the natural parity exchange for the former which is observed experimentally. The parametrization of the Deck background is found not to be critical.

A key feature in our scenario is the presence of the large “ $P + S$ ” amplitude which drives the mechanism. This should be observable both as a decay of the 1.6 GeV state and as a lower-mass enhancement due to the Deck mechanism. Depending on the relative strength of these two terms the resulting mass distribution could be considerably distorted from a conventional Breit-Wigner shape as the Deck peak is broad and the interference could be appreciably greater than in the $\rho\pi$ channel.

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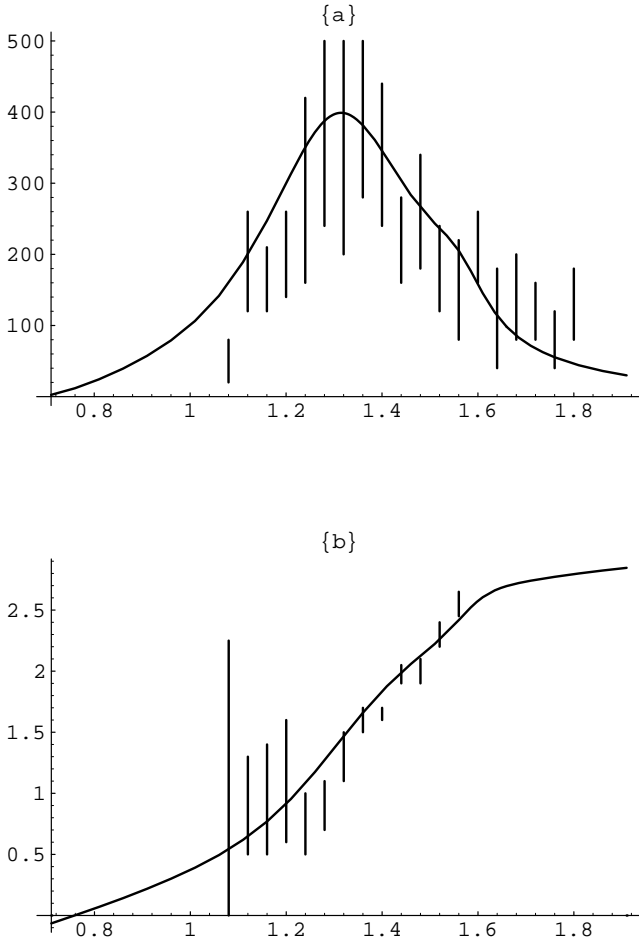


Figure 3: Results of the K-matrix analysis. (a) The events ($|F_1|^2$) in $\eta\pi$ as compared to experiment¹; (b) The phase (of F_1) in $\eta\pi$ compared to experiment¹⁸. The invariant mass w is plotted on the horizontal axis in GeV. When the phase is plotted it is in radians, with the overall phase *ad hoc*. The parameters of the simulation are $m_{\rho} = 1.6$ GeV, $\Gamma_{\rho} = 168$ MeV³, $\gamma_1 = 0.31$, $\gamma_2 = 0.52$, $\gamma_3 = 1.49$, $m_{b1} = 1.32$ GeV, $m_{b2} = 1.23$ GeV, $\gamma_{b1} = 1.53$, $\gamma_{b2} = 2.02$, $V_{b1}/V_{\rho} = 2.05e^{2.77i}$, $V_{b2}/V_{b1} = 0.35e^{1.6i}$. V_{ρ} sets the overall magnitude and phase, which is not shown. None of the ratios of production strengths should be regarded as physically significant, since the K-matrix formalism allows for the introduction of additional parameters in the modelling of the backgrounds, which would change the values of these ratios. The plots shown here are only weakly dependent on the $\rho\pi$ parameters γ_{b2} and V_{b2} . The parameters have been chosen to fit both the $\eta\pi$ data¹ and the preliminary $\rho\pi$ data³. Experiment has not been able to eliminate the possibility that the low mass peak in $\rho\pi$ is due to leakage from the a_1 . The background amplitude in $\rho\pi$ is being used as a means of parametrising all forms of background into the $\rho\pi$ channel, including leakage or Deck.

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