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.

Evidence for a $J^{PC} = 1^{++}$ isovector resonance $\hat{\rho}(1405)$ at 1.4 GeV in the reaction $\pi^- p \to \eta\pi^- p$ has been published recently by the E852 collaboration at BNL. The mass and width quoted are $1370 \pm 16^{+50}_{-30}$ MeV and $385\pm40^{+65}_{-105}$ respectively. These conclusions are strengthened by the claim of the Crystal Barrel collaboration that there is evidence for the same resonance in $pp$ annihilation with a mass of $1400 \pm 20 \pm 20$ MeV and a width of $310 \pm 50^{\pm50}_{-30}$ MeV, 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 $\pi^- N \to \pi^+\pi^-\pi^- N$. The E852 collaboration recently reported evidence for a resonance at $1593 \pm 8^{+29}_{-47}$ MeV with a width of $168 \pm 20^{+150}_{-12}$ MeV, 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.

Recent flux–tube and other model estimates and lattice gauge theory calculations for the lightest 1$^{++}$ hybrid support a mass substantially higher than 1.4 GeV and often above 1.6 GeV. Further, on quite general grounds, it can be shown that a $\eta\pi$ decay of 1$^{++}$ hybrids is unlikely. 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 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. 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.
The \( \eta\pi \) peak in the E852 data spans the \( \rho\pi \) and \( b_1\pi \) thresholds, so we propose a Deck-type model 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 rules which operate on the quark level and have been estimated in QCD sum rules to be tiny (\( \sim 0.3 \) MeV) 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 decay, and it is strongly coupled to \( \eta\pi \) by \( \rho \) 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 mechanism is known to produce broad low–mass enhancements for a particle pair in three–particle final states, for example in \( \pi p \to (\rho\pi)p \). In this latter case, the incident pion dissociates into \( \rho\pi \), either of which can then scatter off the proton. 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 \( \pi \to 0^–, 1^+, 2^–, ... \) (the Gribov–Morrison rule). 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. for the reaction \( \pi p \to (\rho\pi)p \) in which the full \( \pi p \) scattering amplitude was used, so that the effect of exchanges other than the pomeron are automatically 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. It can produce circles in the Argand plot, the origin of which is the Regge phase factor \( \exp\left[-\frac{i\pi\sigma(t_R)}{2}\right] \).

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 contribute. We suggest that in our particular case the relevant processes are (from left to right in Figure 2)

1. \( \pi \to b_1\omega, \omega p \to \pi p \) giving a \( b_1\pi \) final state.
2. \( \pi \to \pi\rho, \rho p \to \eta p \) giving a \( \eta\pi \) final state.
3. \( \pi \to \rho\pi, \pi p \to \pi p \) and \( \rho p \to \rho p \) giving a \( \rho\pi \) final state.

For each of these processes the rescattering will be predominantly via \( \rho \) (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. We find

\( ^{a} \) The use of \( b_1\pi \) is not critical here: any channel with a threshold near 1.4 GeV will suffice.
However, when a non–resonant ηπ in the region 1 – 200 MeV there is no shift of the peak. However, when a non–resonant ηπ P–wave is introduced, the interference between this and the 1.6 GeV state can appear as a 1.4 GeV peak in ηπ.

We have seen that the non–resonant ηπ wave can have significant presence at the b1π threshold, 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 rules the interference effectively shifts the peak in ηπ down from 1.6 GeV to 1.4 GeV. It is not necessary for the 1.6 GeV resonance to have a strong ηπ decay. It is significant that the E852 experiment finds b at 1370 ± 16+50−30 MeV, near the b1π 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 [10]. We assume there to be a ρ with mρ = 1.6 GeV as motivated by the structure observed in pπ [10]. The problem is simplified to the case where there is decay to two observed channels i.e. ηπ and ρπ, 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 unitarity, we assume a real and symmetric 3 × 3 K–matrix. The amplitudes after final–state interactions and production are related by

\[ F = (I - iK)^{-1}P \]  

(1)

We define the widths as

\[ \Gamma_i = \gamma_i^2 \frac{B^2(q_i)}{B^2(q _i^0)} \rho(q_i) \quad i = 1, 2 \]  

(2)

\[ \Gamma_3 = \gamma_3^2 \Gamma \rho(q_3) \]  

(3)

where \( q_i \) is the breakup momentum in channel \( i \) from a state of effective mass \( w \), and \( q_i^0 \) is the breakup momentum in channel \( i \) from a state of effective mass \( m_\rho \). The kinematics is taken care of by use of the phase space factor

\[ \rho(q) = \frac{2q}{w} \]  

(4)

and the P–wave angular momentum barrier factor

\[ B^2(q) = \frac{(q/q_R)^2}{1 + (q/q_R)^2} \]  

(5)

where the range of the interaction is \( q_R = 1 \) fm = 0.1973 GeV.

We assume the experimental width in ρπ of \( \Gamma_\rho = 168 \) MeV[10] to be the total width of the state[10]. We adopt the flux–tube model of Isgur and Paton and use the ρπ and b1π widths which it predicts for a hybrid of mass 1.6 GeV. Since the model predicts that the branching ratio of a hybrid to b1π is 59 – 74 % and to f1π is 12 – 16 %[10], we obtain the P + S–wave width to be 120 – 150 MeV. Analysis of the data shows that the pπ branching ratio of \( \rho(1600) \) is 20 ± 2 %[10], corresponding to a ρπ width of 30 – 37 MeV. This is consistent with flux–tube model predictions of 9 – 22 %[10]. For the simulation we use a b1π width of 120 MeV, a ρπ width of 34 MeV, and an ηπ 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

\[ K_{ij} = \frac{m_\rho \sqrt{\Gamma_i \Gamma_j}}{m_\rho^2 - w^2} + c_{ij} \]  

(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

\footnote{It 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 \( m_{b_1} = 1.32 \) GeV and a width \( \Gamma_{b_1} = 300 \) 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 \( m_{b_2} = 1.23 \) GeV with a width \( \Gamma_{b_2} = 400 \) MeV, which when plotted as an invariant mass distribution effectively peaks at \( \sim 1.15 \) GeV, in agreement with detailed Deck calculations in the \( 1^{++} \) wave 1.

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

\[
c_{11} = \frac{m_{b_1} \Gamma_{b_1}}{m_{b_1}^2 - w^2} \quad c_{22} = \frac{m_{b_2} \Gamma_{b_2}}{m_{b_2}^2 - w^2} \quad (7)
\]

The widths are defined analogously to Eq. 2 as

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

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

The production amplitudes are given by

\[
P_i = \frac{m_\rho V_\rho \sqrt{\frac{1}{\Gamma_{\rho}^2} \Gamma_\rho}}{m_\rho^2 - w^2} + c_i \quad (9)
\]

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

\[
c_1 = \frac{m_{b_1} V_{b_1} \sqrt{\frac{1}{\Gamma_{b_1}^2} \Gamma_{b_1}}}{m_{b_1}^2 - w^2} \quad c_2 = \frac{m_{b_2} V_{b_2} \sqrt{\frac{1}{\Gamma_{b_2}^2} \Gamma_{b_2}}}{m_{b_2}^2 - w^2} \quad (10)
\]

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. 3a and clearly provide a good description of the \( \eta \pi \) data 10.

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 \( \eta \pi \). 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 data 11. The phase motion is also more pronounced in the region between the two peaks than that suggested by the data 12. 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 data 3. 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 \( J^P C = 1^{--} \) \( \eta \pi \) 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 Ball claim for the presence of a similar state at \( 1400 \pm 20 \pm 20 \) MeV in the reaction \( \bar{p}p \to \eta \pi^+ \pi^- \). 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 \( \bar{p}p \) 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 \( \sim "P + S" \) 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.

References
1. D.R. Thompson et al. (E852 Collab.), Phys. Rev. Lett. 79 (1997) 1630.
2. A. Abele et al. (Crystal Barrel Collab.), Phys. Lett. B243 (1998) 175; W. Dünneweber (Crystal Barrel Collab.), Proc. of HADRON’97 (Upton, N.Y., August 1997), p. 309, eds. S.-U. Chung, H.J. Willutzki.
3. N.M. Cason (E852 Collab.), Proc. of Intersections between Nuclear and Particle Physics, p. 471 (Big Sky, Montana, May 1997), ed. T.W. Donnelly, American Institute of Physics; D.P. Weygand and A.I. Ostrovidov (E852 Collab.), Proc. of HADRON’97 (Upton, N.Y., August 1997), p. 313, 263, eds. S.-U. Chung, H.J. Willutzki; A.I. Ostrovidov et al. (E852 Collab.), in preparation.
4. Yu.P. Gouz. et al. (VES Collab.), Proc. of the 26th ICHEP (Dallas, 1992), p. 572, ed. J.R. Sanford.
5. D. Ryabchikov (E852 Collab.), “Study of the reaction $\pi^- p \rightarrow \eta\pi^- p$ in E852 experiment”, Proc. of HADRON’97 (Upton, N.Y., August 1997), p. 527, eds. S.-U. Chung, H.J. Willutzki; Yu. P. Gouz. et al. (VES Collab.), Proc. of the 26th ICHEP (Dallas, 1992), p. 572, ed. J.R. Sanford.
6. P.R. Page, Phys. Lett. B415 (1997) 205.
7. T. Barnes, F.E. Close and E.S. Swanson, Phys. Rev. D52 (1995) 5242.
8. C. Michael et al., Nucl. Phys. B347 (1990) 854; Phys. Lett. B142 (1984) 291; Phys. Lett. B129 (1983) 351; Liverpool Univ. report LTH-286 (1992), Proc. of the Workshop on QCD : 20 Years Later (Aachen, 9–13 June 1992).
9. P.R. Page, Phys. Lett. B401 (1997) 313; F. Iddir et al., Phys. Lett. B207 (1988) 325; H.J. Lipkin, Phys. Lett. 219 (1989) 99.
10. P.R. Page, Proc. of HADRON’97 (Upton, N.Y., August 1997), p. 121, eds. S.-U. Chung, H.J. Willutzki, hep-ph/9711241; P.R. Page, E.S. Swanson, A.P. Szczepaniak, in preparation.
11. G. Ascoli et al. Phys. Rev. D8 (1973) 3894; ibid. D9 (1974) 1963.
12. J.I. Latorre et al., Z. Phys. C34 (1987) 347; S. Narison, “QCD spectral sum rules”, Lecture Notes in Physics, Vol. 26 (1980), p. 369; J. Govaerts, F. de Viron, Phys. Rev. Lett. 53 (1984) 2207.
13. L. Stodolsky, Phys. Rev. Lett. 18 (1967) 973.
14. V. Gribov, Sov. J. Nucl. Phys. 5 (1967) 138; M.R.O. Morrison, Phys. Rev. 165 (1968) 1699.
15. M.G. Bowler et al., Nucl. Phys. B97 (1975) 227; M.G. Bowler, J. Phys. G5 (1979) 203.
16. P.R. Page, Phys. Lett. B402 (1997) 183.
17. I.J.R. Aitchison, Nucl. Phys. A189 (1972) 417; S.-U. Chung et al., Ann. der Phys. 4 (1995) 404.
18. S.-U. Chung, Private communication; Proc. of Jefferson Lab / NCSU Workshop on Hybrids and Pho.
toproduction Physics (1997).