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A possible interpretation of the $\pi_1(1400)$ exotic meson

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Abstract. I will discuss the current theoretical and experimental status of exotic mesons and a possible interpretation of the light, $\pi_1(1400)$ exotic meson as a final state interaction effect.

PACS. 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 13.60.Le Meson production

1 Introduction

Gluonic excitations are expected to play a crucial role in light-quark spectroscopy by providing information on dynamical features of confinement. Strong interactions between colored gluons could result in a spectrum of gluon-dominated mesons —glueballs as well as hybrid states characterized by the presence of simultaneous gluonic and quark excitations. There is indeed strong evidence that the scalar-isoscalar π-π spectrum in the 1–2 GeV mass region has more states then expected from the valence quark model. The decay pattern of three scalar resonances observed in this mass region is consistent with the existence of a $J^{PC} = 0^{++}$ glueball with mass around 1.5 GeV. The possible mixing with ordinary mesons, however, makes the identification of glueballs and hybrids problematic with the exception of exotic states. These are mesons which have quantum numbers, J^{PC} that cannot originate from the valence quark and antiquark alone, *e.g.* $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$. There is good evidence from lattice computations that the additional contribution to an exotic meson structure should come from exciting the gluonic field rather than from breakup channels, *e.g.* $(Q\bar{Q})^2$.

The spectrum of gluonic excitations and its connection to confinement has been extensively studied on the lattice. Numerical simulations of the energy of a static quark-antiquark system in the presence of dynamical gluons result in a linearly rising potential between the quarks —a characteristic feature of a confining interactions. There also exist lattice simulations of $Q\bar{Q}$ energies in the presence of excited gluon configurations. The first-excited state of the gluonic field turns out to have one unit of the total angular momentum along the axis connecting the static color sources, and has a negative product of parity and charge conjugation [1]. Combining the quantum numbers of the low-lying gluon excitation with those of the quark-antiquark pair leads to a spectrum of hybrid mesons including the exotic $J^{PC} = 1^{-+}$ state which arises from combining the orbitally excited gluon field with the $L = 0, S = 1$ quark-antiquark configuration. From lattice simulations of light-quark exotics it follows that the mass of the 1^{-+} state is slightly below 2 GeV [2–4]. Similarly, studies of the charmonium exotics indicate that the excitation of the gluonic degrees of freedom requires approximately 1 GeV. One should keep in mind, however, that the masses computed on the lattice are obtained with rather heavy u- and d-quark masses, > 50 MeV. Extrapolation to the chiral limit can shift downward the predicted hadron masses by 100–200 MeV [5]. An identification of exotic resonances can only be made if they are not too broad. This is indeed expected to be the case based on studies of exotic-mesons widths in the large-N_C limit [6]. Studies of the ground-state exotic-meson wave function on the lattice also show that it is well confined to a region where pair creation and string breaking are not expected to be significant [7].

To summarize, the current lattice and phenomenological studies indicate that the lightest exotic meson should have $J^{PC} = 1^{-+}$, mass between 1.8–2 GeV and a typical hadronic width of 100–200 MeV.

2 The $\eta\pi$ spectrum

Recently, a few exotic-mesons candidates have been reported, mainly by the E852 Collaboration. Some of the reported states, however, do not fit the theoretical profile discussed above. The E852 Collaboration reported a 1^{-+} exotic resonance in $\eta\pi^-$ and $\eta'\pi^-$ decay channels with widths of the order of 350 MeV and masses 1.4 and 1.6 GeV, respectively. The experiment used 18 GeV π^- beam on a hydrogen target and resonances were identified via the partial-wave analysis [8]. The Crystal Barrel experiment also found a signature of an exotic wave in

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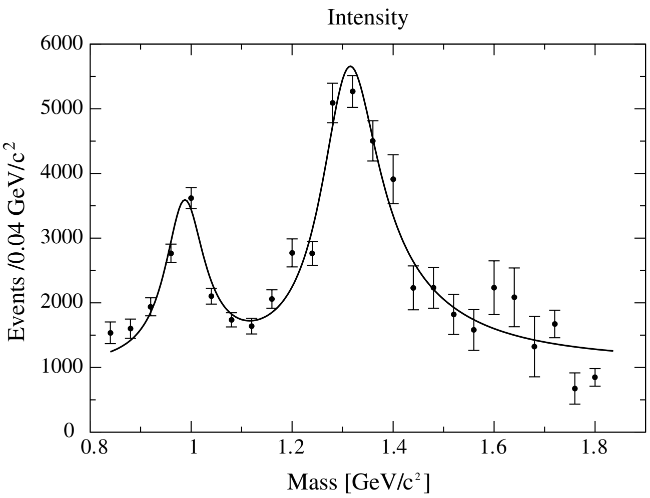

Fig. 1. Acceptance-corrected mass distribution of the $\eta\pi^0$ system for momentum transfer $t < 0.3$ GeV^2, from the reaction $\pi^-(18 \text{ GeV})p \rightarrow \eta\pi^0 n$.

the $\eta\pi$ system consistent with the E852 result [9]. The $\eta\pi$ channel is particularly suited for exotic-meson identification, since the $\eta\pi$ P-wave has exotic quantum numbers. The resonance interpretation of the exotic wave in the $\eta\pi^-$ channel came from mass-dependent fits of the intensity and phase motion of the natural-parity P-waves. However, if the spin-1 exotic resonance is to be directly produced in the reaction

$$\pi^- p \rightarrow X^- p \rightarrow \eta\pi^- p\,, \tag{1}$$

it should be also found with the same mass and width in unnatural-parity exchange P-waves, P_- and P_0, even if the underlying production mechanisms are different.

More recently an analysis of the $\eta\pi^0$ spectrum has been performed [10]. The neutral channel has the added advantage of having well-defined charge conjugation. The final $\eta\pi^0$ data sample has approximately 35K events, and was comparable to the $\eta\pi^-$ sample discussed above. The $\eta\pi^0$ mass spectrum, shown in fig. 1 clearly indicates presence of the $a_0(980)$- and the $a_2(1320)$-resonances. The momentum transfer, $t-$ distribution of the D-waves representing the a_2 production were found consistent with the Regge exchange of ρ (natural) and b_1 mesons (unnatural). Limited statistics prevented t-dependent analysis for the a_0, however qualitatively it was also found consistent with the expected helicity-non-flip production. In the Gottfried-Jackson frame the η (or π^0) distribution can be written as

$$I(\Omega) = \sum_{\epsilon} \left| \sum_{L,M} a^{\epsilon}_{LM}(M_{\eta\pi^0}, t) Y^{\epsilon}_{LM}(\Omega) \right|^2, \tag{2}$$

where $0 < M \leq 1$ is the magnitude of the magnetic quantum number, $\epsilon = \pm$ labels the naturality (or reflectivity) of an amplitude, and Y^ϵ is the real or imaginary part of a spherical harmonic for $\epsilon = 1, -1$, respectively. In each mass, $M_{\eta\pi^0}$ and momentum transfer, t-bin there are seven complex amplitudes corresponding to $S = a_{00}$, $P_0 = a_{10}$, $P_+ = a^+_{11}$, $P_- = a^-_{11}$, and D_0, D_+ and D_-. Empirically the $D^\epsilon_2 = a^\epsilon_{22}$ waves were found to be negligible. Magnitudes and phases of these waves can be determined by fitting the angular distribution, $I(\Omega)$ or its moments. It is however well know that there are multiple sets of amplitudes which give identical intensity function, I. For this reason physical constraints have to be imposed on the amplitudes to eliminate the ambiguities. We have found that one can uniquely (modulo a few mass and t-bins) select the solution by imposing the requirement that all waves are continuous, the S dominates at threshold and is small at the a_2 region where the D-waves are large, and that the $D_0 - S$ phase motion corresponds to the interference of two resonances.

One can also study the mass dependence of the individual waves by fitting the mass distribution of moments, defined by

$$H_{LM} = \int \mathrm{d}\Omega I(\Omega) Y^*_{LM}(\Omega) \tag{3}$$

which, since given directly by the data, are unambiguous. The mass dependence of an individual wave was parameterized using a relativistic Breit-Wigner (BW) form consistent with the assumption that the spectrum can be described by an a_0, a_2 and an exotic P-wave resonance.

We have found that while the a_0- and a_2-resonance parameters are well reproduced, no consistent set of parameters of the P-wave resonance could be found for the P-waves. We should also point out that the natural-parity P_+-wave was found consistent with the one from the $\eta\pi^-$ analysis discussed earlier.

The difference in the interpretation of the observed P-wave is based on the type of analysis (fits) of the data. The resonance interpretation of ref. [8] was based on a fit to the P_+- and D_+-wave intensity, and the $P_+ - D_+$ phase differences in a single t-bin. No results were shown for different t-regions, other, unnatural P-wave amplitudes nor comparison of the fit to the amplitudes with the experimental moments. In contrast, our analysis takes all the above under consideration and then we find that resonance interpretation becomes problematic. This is illustrated, for example, in fig. 2 where the $H(10)$ moment, which is linear in the P-wave, is shown. The experimental data points prefer a "flatter" P-wave solution (solid line) as compared with the more varying one (dashed).

We also conclude that the data indeed indicate the presence of a P-wave but with a weak mass-dependence, while the "bump" structure seen in the P_+-wave in ref. [8] (in both $\eta\pi^0$ and $\eta\pi^-$) channels is most likely due to an imperfect acceptance and "leakage" from the dominant D_+-wave.

It has recently been shown that the observed light 2-meson spectra below 1–1.5 GeV can be well described by an effective, energy-independent interaction supplemented in some channels by direct coupling to a few underlying QCD states, *e.g.* the ρ in the $\pi\pi$, $I = S = 1$ channel [11–13]. These effective interactions in some cases, *e.g.* $\pi\pi$ $I = S = 0$, are well constrained by chiral symmetry while in others, *e.g.* $\pi\eta$ in the P-wave are more phenomenological [14]. The notion of a QCD resonance comes, in turn from the leading behavior of the meson spectrum in the

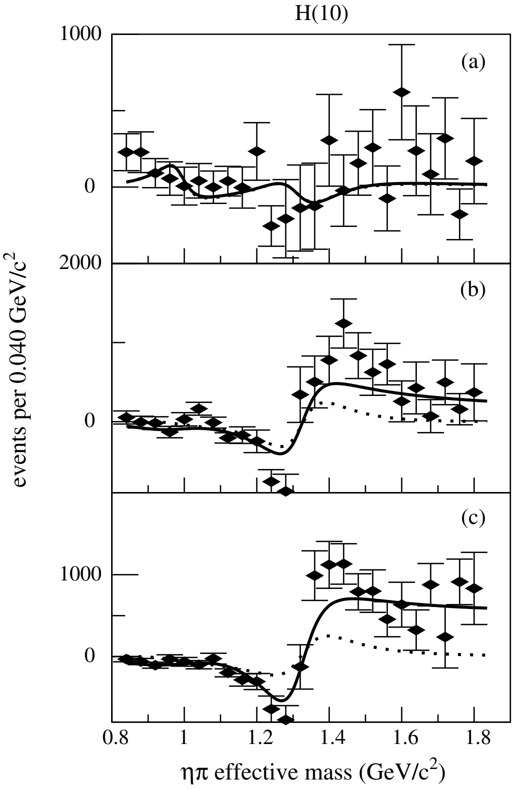

Fig. 2. Acceptance-corrected $H(10)$ moment, in three t-regions (a, b, c) of the $\eta\pi^0$ angular distribution as a function of the $\eta\pi^0$ invariant mass.

large-N_C limit where the meson loops are suppressed while quark bound states are expected to exist.

The E852 data in both $\eta\pi^0$ and $\eta\pi^-$ channels indicate that the P-wave phase is positive and slowly rising as a function of the $\eta\pi$ mass. Even though, as discussed above, this behavior cannot be unambiguously attributed to a simple BW pole on the complex energy plane near the real axis, the behavior can be due to a residual attractive interaction.

We thus assume that in the process,

$$\pi^- p \to \eta\pi^0 n \tag{4}$$

the $\eta\pi^0$ is directly produced with a slowly (or no) mass-dependent phase and then the observed P-wave phase comes from $\eta\pi^0 \to \eta\pi^0$ rescattering.

For illustration purposes consider a simple model for the $\eta\pi$ interaction given by a separable potential in the P channel of the form

$$\langle\eta\pi, q|V|\eta\pi, p\rangle = 4\pi\lambda\frac{qp}{f_\pi^2}g(p)g(q)\,. \tag{5}$$

The scale f_π is natural for low-energy meson-meson interactions and λ is a coupling constant of $O(1)$. Even though to lowest order in chiral expansion the P-wave $\eta\pi$ potential vanishes, one can expect the η_0-η_8 mixing effects to produce an effective interaction of the order $O(p^2/f_\pi^2)$ [14]. The form factors $g(p)$ are thus expected to cut off the interaction at a scale of the order of $4\pi f_\pi \sim 1$ GeV. The

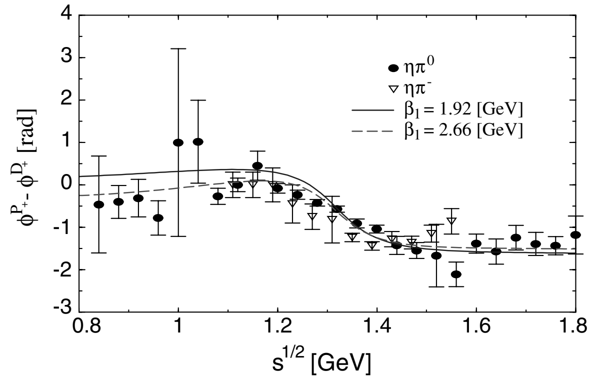

Fig. 3. Comparison of $P_+ - D_+$ wave phase differences with the $\eta\pi$ phase calculated using an effective interaction of eq. (5) with two different momentum cutoffs.

general features of the potential can also be inferred, for example by fitting the $S = I = 0$ $\pi\pi$ spectrum, where no QCD resonances are expected below 1.3 GeV. Comparison of the $\eta\pi$ elastic phase shift calculated using the above interaction with the $\eta\pi^0$ and $\eta\pi^-$ data is shown in fig. 3.

A more elaborate study of the rescattering effects, taking into account constraints from chiral symmetry and coupling to other channels are currently being investigated.

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