International Journal of Modern Physics A

Analysis of $J^{PC} = 1^{-+}$ Exotic Hybrid $\eta\pi$, $\eta'\pi$ Decays

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Received (Day Month Year)
Revised (Day Month Year)

Investigations of the mass and decays of the $J^{PC} = 1^{-+}$ hybrid are reviewed, including calculation of the $\pi_1(1^{-+}) \to \eta\pi$, $\eta'\pi$ decay widths within the QCD sum rules technique. In this calculation, the recently-proposed η, η' quark mixing scheme is employed. The results indicate that the decay width $\Gamma_{\pi_1 \to \eta\pi} \approx 250$ MeV is large compared with the decay width $\Gamma_{\pi_1 \to \eta'\pi} \approx 20$ MeV. Inspired by these results, some phenomenological approaches are suggested to gain an understanding of the underlying mechanism of $\eta\pi$ and $\eta'\pi$ hybrid decays.

Keywords: Hybrids; Sum rules; Decay.

The property of asymptotic freedom enables Quantum Chromodynamics (QCD) to provide an excellent description of short-distance strong-interaction processes in terms of fundamental interactions between quarks and gluons, but presents significant challenges for the description of long-distance soft processes. Quark models (such as potential and bag models) provide a good picture for the structure of hadrons, but the mechanism of confinement and generation of masses in such models is not fully understood. Furthermore, direct application of QCD to hadrons as bound states of quarks and gluons has not been achieved completely, and the relation between QCD and quark models is not fully elucidated. The study of gluon freedom may give some hints at a solution to these problems.

Despite the general success of quark models for conventional $q\bar{q}$ mesons and qqq baryons, some hadrons in the low and medium energy region (1–2.5 GeV) are difficult to explain as conventional hadrons. Exotic hadrons such as glueballs (composed purely of gluons), hybrids (quark and gluonic combinations), and multi-quark states of more than three constituent quarks have been proposed to explain these hadrons. Study of these exotic states can lead to a greater understanding of the non-perturbative low energy dynamics of QCD.

Neutral $q\bar{q}$ mesons have quantum numbers of parity and charge conjugation

J^{PC} given by $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$; they cannot have exotic quantum numbers such as 0^{+-}, 1^{-+}, 2^{+-}, ... Such exotic quantum numbers could only be achieved via exotic hadronic states.

The lowest-lying hybrid is predicted to be the $J^{PC} = 1^{-+}$ state. The spectrum and the decays of this exotic hybrid have been studied in many models. The MIT bag model predicts a mass in the range 1.4–1.8 GeV,[1] and the flux tube model predicts a mass of approximately 1.7 GeV along with the decay mode predictions $\pi_1 \to [b_1(1235)\pi]_S \approx 150$ MeV, $\pi_1 \to [f_1(1235)\pi]_S \approx 40$ MeV, $\pi_1 \to \eta\pi,\ \eta'\pi \approx 0$.[2] Further flux tube model decay width predictions include $\pi_1 \to b_1\pi \approx 24$ MeV, $\pi_1 \to f_1\pi \approx 5$ MeV, $\pi_1 \to \rho\pi \approx 9$ MeV, $\pi_1 \to \eta\pi,\ \eta'\pi \approx 0$.[3] Within the QCD sum rules technique, the mass predictions are in the 1.4–2.1 GeV range, with decay mode calculations of $\pi_1 \to \rho\pi \approx 274$ MeV, $\pi_1 \to \eta'\pi \approx 3$ MeV.[4] Finally, lattice gauge theory results in a mass prediction of about 2.0 GeV.[5] There are some analyses with other methods, which will not be mentioned here because of space limitations.

In experiments, the most likely candidates for 1^{-+} exotic hybrids, the $\pi_1(1600)$ and $\pi_1(1400)$, have been observed by many groups. The $\pi_1(1400)$ was observed by E852 and Crystal Barrel collaboration in the $\eta\pi$ final states with width $\Gamma > 300$ MeV.[6,7] The $\pi_1(1600)$ was observed not only in $\rho\pi$ final states with width $\Gamma = 168 \pm 20^{+150}_{-12}$ MeV but also in $\eta'\pi$ final states with width $\Gamma = 340 \pm 40 \pm 50$ MeV by E852.[8,9] If these observations truly represent an 1^{-+} exotic hybrid, then the experimental signal is obviously inconsistent with theoretical predictions. Furthermore, experimental evidence for glueball and multi-quark states candidates[10,11] will open the Pandora's box for the mixing among them, further complicating the analyses. So far, no one exotic hadron has been pinned down definitely, and clear identification and explanation of these exotic states will present experimental and theoretical challenges.

As described below, we have re-analyzed the channels $\pi_1(1^{-+}) \to \eta\pi,\ \eta'\pi$ using QCD sum-rule techniques which incorporate a quark-mixing scheme[15] for $\eta,\ \eta'$.[13] Inspired by these results, we have examined the implications of two possible assumed decay mechanisms of hybrids in the ratio of decay widths.[14]

QCD sum rule techniques[12] are an effective non-perturbative method which relates fundamental parameters of QCD to hadronic parameters. To calculate the channels $\pi_1(1^{-+}) \to \eta\pi,\ \eta'\pi$, the hybrid interpolating current was chosen as $j_\mu(x) = g\bar{q}\gamma^\alpha G^a_{\alpha\mu}T^a q$. QCD sum-rule analysis of the three point correlator

$$\Gamma_\mu(p,q) = i\int d^4x d^4y e^{i(qx+py)}\langle 0|T(j_\pi(x) j_{\eta'}(y) j_\mu(0))|0\rangle \qquad (1)$$

with the anomalous current $j_{\eta'}(x) = -\frac{3\alpha_s}{4\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + 2\sum_{u,d,s} m_i\bar{q}\gamma_5 q$ results in $\Gamma(\pi_1 \to \eta\pi) = 0$ and $\Gamma(\pi_1 \to \eta'\pi) \sim 3$ MeV.[4]

It is well known that the $\eta(548)$ and $\eta'(958)$ are mixed states. In the quark mixing scheme, the orthogonal flavor basis was chosen as

$$\eta_q = q\bar{q} = (u\bar{u} + d\bar{d})/\sqrt{2} \quad , \quad \eta_s = s\bar{s},$$

and

$$\eta = \cos\phi\eta_q - \sin\phi\eta_s\ ,\ \eta' = \sin\phi\eta_q + \cos\phi\eta_s .$$

where $\phi = 39.3^\circ \pm 1.0^\circ$.[15]

In order to take account of the η, η' mixing in our sum rules calculation, we used

$$j^q_{5\mu} = \frac{1}{\sqrt{2}}(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)\ ,\ j^s_{5\mu} = \bar{s}\gamma_\mu\gamma_5 s$$

in construction of the three point correlator

$$\Gamma_\mu(p,q) = i\int d^4x d^4y e^{i(qx+py)}\langle 0|T(j_\pi(x)\partial_\nu j^{q,s}_{5\nu}(y)j_\mu(0))|0\rangle. \quad (2)$$

and obtained $\Gamma(\pi_1 \to \eta'\pi) \sim 21$ MeV and $\Gamma(\pi_1 \to \eta\pi) \sim 250$ MeV in a consistent fashion.[13] We note that in this calculation, the decay width $\pi_1 \to \eta\pi$ is much larger than that of $\pi_1 \to \eta'\pi$.

Can we find some hints about the mechanism of hybrid decays through the study of $\pi_1 \to \eta\pi,\ \eta'\pi$? Let us first consider the radiative decays of $J/\psi \to \eta\gamma,\ \eta'\gamma$ and $\phi \to \eta\gamma,\ \eta'\gamma$. We have the experimental values[16]

$$\frac{\Gamma(J/\psi \to \eta\gamma)}{\Gamma(J/\psi \to \eta'\gamma)} = 0.200 \pm 0.023\ ,\ \frac{\Gamma(\phi \to \eta'\gamma)}{\Gamma(\phi \to \eta\gamma)} = 4.7 \pm 0.47 \pm 0.31 \times 10^{-3}.$$

As is known, the radiative decay of J/ψ could be thought to occur through $\bar{c}c \to gg \to \eta\gamma,\ \eta'\gamma$, resulting in[14]

$$\frac{\Gamma(J/\psi \to \eta\gamma)}{\Gamma(J/\psi \to \eta'\gamma)} \simeq \left|\frac{\langle 0|G\tilde{G}|\eta\rangle}{\langle 0|G\tilde{G}|\eta'\rangle}\right|^2 \left(\frac{1 - m^2_\eta/m^2_{J/\psi}}{1 - m^2_{\eta'}/m^2_{J/\psi}}\right)^3 ,$$

where the gg pair is assumed sufficiently hard and the use of the local operator $G\tilde{G} = 1/2\epsilon^{\mu\nu\lambda\rho}G^a_{\lambda\rho}G^a_{\mu\nu}$ extracted from the gg pair is a good approximation.

Alternatively, the radiative decay of ϕ could be thought to occur through $\bar{s}s \to \eta\gamma,\ \eta'\gamma$,[14] resulting in

$$\frac{\Gamma(\phi \to \eta'\gamma)}{\Gamma(\phi \to \eta\gamma)} \simeq \left|\frac{\langle 0|\bar{s}i\Gamma_5 s|\eta'\rangle}{\langle 0|\bar{s}i\Gamma_5 s|\eta\rangle}\right|^2 \left(\frac{1 - m^2_{\eta'}/m^2_\phi}{1 - m^2_\eta/m^2_\phi}\right)^3 .$$

In fact, these approximations involving couplings to different operators are related to the radiative J/ψ and ϕ decay mechanisms. Correspondingly, there exist two possible decay mechanisms for hybrids. The physical picture is that the couplings through two different operators may correspond to two different hybrid decay mechanisms. One corresponds to quark fragmentation into two gluons (denoted by gg), and the other corresponds to gluon fragmentation into a quark and an anti-quark (denoted by $q\bar{q}$). If these approximations are valid, then we can detect these two different decay mechanisms directly through the ratio of decay widths.

When the decay $\pi_1 \to \eta\pi,\ \eta'\pi$ occur through $\pi_1 \to gg \to \eta\pi,\ \eta'\pi$, we have[14]

$$\frac{\Gamma(\pi_1 \to \eta\pi)}{\Gamma(\pi_1 \to \eta'\pi)} \simeq \left|\frac{\langle 0|G\tilde{G}|\eta\rangle}{\langle 0|G\tilde{G}|\eta'\rangle}\right|^2 \left(\frac{1-m_\eta^2/m_{\pi_1}^2}{1-m_{\eta'}^2/m_{\pi_1}^2}\right)^3,$$

while a decay $\pi_1 \to \eta\pi,\ \eta'\pi$ through $\pi_1 \to q\bar{q} \to \eta\pi,\ \eta'\pi$ results in[14]

$$\frac{\Gamma(\pi_1 \to \eta\pi)}{\Gamma(\pi_1 \to \eta'\pi)} \simeq \left|\frac{\langle 0|\bar{s}i\Gamma_5 s|\eta'\rangle}{\langle 0|\bar{s}i\Gamma_5 s|\eta\rangle}\right|^2 \left(\frac{1-m_\eta^2/m_{\pi_1}^2}{1-m_{\eta'}^2/m_{\pi_1}^2}\right)^3.$$

From our results, the decay of $\pi_1 \to \eta\pi,\ \eta'\pi$ seems to occur through $q\bar{q}$ mechanism, which means that the quark in light hybrids is not hard enough to fragment into two gluons.[13,14] To verify the relation between the decay mechanism and decay widths, more decay channels should be analyzed. More importantly, the decay widths and branching ratios of hybrids should be measured.

Acknowledgments

Ailin Zhang is supported by National Science Foundation of China, and T. G. S is grateful for research support from the Natural Sciences and Engineering Research Council of Canada (NSERC).

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