THE $\eta(1405)$, $\eta(1475)$, $f_1(1420)$, AND $f_1(1510)$

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The first observation of the $\eta(1440)$ was made in $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \to K\overline{K}\pi$ [1]. This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ was also observed in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [2–4] and $\gamma\rho$ [5]. There is evidence for the existence of two pseudoscalars in this mass region, the $\eta(1405)$ and $\eta(1475)$. The former decays mainly through $a_0(980)\pi$ (or direct $K\overline{K}\pi$) and the latter mainly to $K^*(892)\overline{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: π^-p [6,7]; radiative $J/\psi(1S)$ decay [8,9]; and $\overline{p}p$ annihilation at rest [10–13]. All of them give values for the masses, widths, and decay modes in reasonable agreement. However, Ref. 9 favors a state decaying into $K^*(892)\overline{K}$ at a lower mass than the state decaying into $a_0(980)\pi$. In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\overline{K}\pi$ through $a_0(980)\pi$, and hence a signal is also expected in the $\eta\pi\pi$ mass spectrum. This was indeed observed by MARK III in $\eta\pi^+\pi^-$ [14], which reports a mass of 1400 MeV, in line with the existence of the $\eta(1405)$ decaying into $a_0(980)\pi$.

BES [15] reports an enhancement in $K^+K^-\pi^0$ around 1.44 GeV in $J/\psi(1S)$ decay, recoiling against an ω (but not a ϕ) without resolving the presence of two states nor performing a spin-parity analysis, due to low statistics. This state could also be the $f_1(1420)$ (see below). On the other hand, BES observes $\eta(1405) \to \eta\pi\pi$ in $J/\psi(1S)$ decay, recoiling against an ω [16].

The $\eta(1405)$ is also observed in $\overline{p}p$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$, where it decays into $\eta\pi\pi$ [17]. The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ signal, in agreement with MARK III [14] and DM2 [4].

However, the issue remains controversial as to whether two pseudoscalar mesons really exist. According to Ref. 18 the splitting of a single state could be due to nodes in the decay amplitudes which differ in $\eta\pi\pi$ and $K^*(892)\overline{K}$. Based on the isospin violating decay $J/\psi(1S) \to \gamma 3\pi$ observed by BES [19] the splitting could also be due to a triangular singularity mixing $\eta\pi\pi$ and $K^*(892)\overline{K}$ [20–21]. However, in a further paper [22], using the approach of [20], the authors concluded that the BES results can be reproduced either with the $\eta(1405)$ or the $\eta(1475)$or by a mixture of the two states.

The $\eta(1295)$ has been observed by four $\pi^- p$ experiments [7,23–25], and evidence is reported in $\overline{p}p$ annihilation [26–28]. In $J/\psi(1S)$ radiative decay, an $\eta(1295)$ signal is evident in the 0^{-+} $\eta\pi\pi$ wave of the DM2 data [9]. Also BaBar [29] reports evidence for a signal around 1295 MeV in B decays into $\eta\pi\pi K$. However, the existence of the $\eta(1295)$ is questioned in Refs. [18] and [30]. The authors claim a single pseudoscalar meson in the 1400 MeV region. This conclusion is based on properties of the wave functions in the $^3P_0$ model (and on an unpublished analysis of the annihilation $\bar{p}p \to 4\pi\eta$). The pseudoscalar signal around 1400 MeV is then attributed to the first radial excitation of the η.

Assuming establishment of the $\eta(1295)$, the $\eta(1475)$ could be the first radial excitation of the η', with the $\eta(1295)$ being the first radial excitation of the η. Ideal mixing, suggested by the $\eta(1295)$ and $\pi(1300)$ mass degeneracy, would then imply that the second isoscalar in the nonet is mainly $s\overline{s}$, and hence couples to $K^*\overline{K}$, in agreement with properties of the $\eta(1475)$. Also, its width matches the expected width for the radially excited $s\overline{s}$ state [31,32]. A study of radial excitations of pseudoscalar mesons [33] favors the $s\bar{s}$ interpretation of the $\eta(1475)$. However, due to the strong kinematical suppression the data are not sufficient to exclude a sizeable $s\bar{s}$ admixture also in the $\eta(1405)$.

The $K\overline{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions by L3 [34]. The analysis led to a clear $\eta(1475)$ signal in $K\overline{K}\pi$, decaying into $K^*\overline{K}$, very well identified in the untagged data sample, where contamination from spin 1 resonances is not allowed. At the same time, L3 [34] did not observe the $\eta(1405)$, neither in $K\overline{K}\pi$ nor in $\eta\pi\pi$. The observation of the $\eta(1475)$, combined with the absence of an $\eta(1405)$ signal, strengthens the two-resonances hypothesis. Since gluonium production is presumably suppressed in $\gamma\gamma$ collisions, the L3 results [34] suggest that $\eta(1405)$ has a large gluonic content (see also Refs. [35] and [36]) .

The L3 result is somewhat in disagreement with that of CLEO-II, which did not observe any pseudoscalar signal in $\gamma\gamma \rightarrow \eta(1475) \rightarrow K_S^0 K^\pm \pi^\mp$ [37]. However, more data are required. Moreover, after the CLEO-II result, L3 performed a further analysis with full statistics [38], confirming their previous evidence for the $\eta(1475)$. The CLEO upper limit [37] for $\Gamma_{\gamma\gamma}(\eta(1475))$, and the L3 results [38], are consistent with the world average for the $\eta(1475)$ width.

BaBar [29] also reports the $\eta(1475)$ in B decays into $K\bar{K}^*$ recoiling against a K, but upper limits only are given for the $\eta(1405)$. As mentioned above, in B decays into $\eta\pi\pi K$ the $\eta(1295) \rightarrow \eta\pi\pi$ is observed while only upper limits are given for the $\eta(1405)$. The $f_1(1420)$ (and the $f_1(1285)$) are not seen.

The gluonium interpretation for the $\eta(1405)$ is not favored by lattice gauge theories which predict the 0^{-+} state above 2 GeV [39,40] (see also the article on the "Quark model" in this issue of the Review). However, the $\eta(1405)$ is an excellent candidate for the 0^{-+} glueball in the fluxtube model [41]. In this model, the 0^{++} $f_0(1500)$ glueball is also naturally related to a 0^{-+} glueball with mass degeneracy broken in QCD. Also, Ref. [42] shows that the pseudoscalar glueball could lie at a lower mass than predicted from lattice calculation. In this model the $\eta(1405)$ appears as the natural glueball candidate, see also Refs. [43–45]. A detailed review of the experimental situation is available in Ref. 46.

Let us now deal with 1^{++} isoscalars. The $f_1(1420)$, decaying into $K^*\overline{K}$, was first reported in $\pi^- p$ reactions at 4 GeV/c [47]. However, later analyses found that the 1400–1500 MeV region was far more complex [48–50]. A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [8] shows the $f_1(1420)$ decaying into $K^*\overline{K}$. Also, a C=+1 state is observed in tagged $\gamma\gamma$ collisions (*e.g.*, Ref. 51).

In $\pi^- p \rightarrow \eta\pi\pi n$ charge-exchange reactions at 8–9 GeV/c the $\eta\pi\pi$ mass spectrum is dominated by the $\eta(1440)$ and $\eta(1295)$ [23,52], and at 100 GeV/c Ref. [24] reports the

$\eta(1295)$ and $\eta(1440)$ decaying into $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ signal, and no evidence for the $f_1(1420)$.

Axial (1^{++}) mesons are not observed in $\overline{p}p$ annihilation at rest in liquid hydrogen, which proceeds dominantly through S-wave annihilation. However, in gaseous hydrogen, P-wave annihilation is enhanced and, indeed, Ref. 11 reports $f_1(1420)$ decaying into $K^*\overline{K}$. The $f_1(1420)$, decaying into $K\overline{K}\pi$, is also seen in pp central production, together with the $f_1(1285)$. The latter decays via $a_0(980)\pi$, and the former only via $K^*\overline{K}$, while the $\eta(1440)$ is absent [53,54]. The $K^0_S K^0_S \pi^0$ decay mode of the $f_1(1420)$ establishes unambiguously C=+1. On the other hand, there is no evidence for any state decaying into $\eta\pi\pi$ around 1400 MeV, and hence the $\eta\pi\pi$ mode of the $f_1(1420)$ must be suppressed [55].

We now turn to the experimental evidence for the $f_1(1510)$. Two states, the $f_1(1420)$ and $f_1(1510)$, decaying into $K^*\overline{K}$, compete for the $s\overline{s}$ assignment in the 1^{++} nonet. The $f_1(1510)$ was seen in $K^-p \rightarrow \Lambda K\overline{K}\pi$ at 4 GeV/c [56], and at 11 GeV/c [57]. Evidence is also reported in π^-p at 8 GeV/c, based on the phase motion of the 1^{++} $K^*\overline{K}$ wave [50]. A somewhat broader 1^{++} signal is also observed in $J/\psi(1S) \rightarrow \gamma\eta\pi^+\pi^-$ [58] as well as a small signal in $J/\psi(1S) \rightarrow \gamma\eta'\pi^+\pi^-$, attributed to the $f_1(1510)$ [59].

The absence of $f_1(1420)$ in K^-p [57] argues against the $f_1(1420)$ being the $s\overline{s}$ member of the 1^{++} nonet. However, the $f_1(1420)$ was reported in K^-p but not in π^-p [60], while two experiments do not observe the $f_1(1510)$ in K^-p [60,61]. The latter is also not seen in central collisions [54], or $\gamma\gamma$ collisions [62], although, surprisingly for an $s\overline{s}$ state, a signal is reported in 4π decays [63]. These facts lead to the conclusion that $f_1(1510)$ is not well established [64].

Assigning the $f_1(1420)$ to the 1^{++} nonet, one finds a nonet mixing angle of $\sim 50°$ [64]. However, arguments favoring the $f_1(1420)$ being a hybrid $q\overline{q}g$ meson, or a four-quark state, were put forward in Refs. [65] and [66], respectively, while Ref. 67 argued for a molecular state formed by the π orbiting in a P-wave around an S-wave $K\overline{K}$ state. The $f_1(1420)$ could also be an isoscalar $K^*\bar{K}$ molecule. It is interesting to note that evidence for an isovector 1^{++} partner, $a_1(1420)$ decaying into $f_0(980)\pi$, was reported recently by the COMPASS experiment in $\pi^- p \rightarrow (3\pi)^- p$ with 190 GeV/c pions [68].

Summarizing, there is convincing evidence for the $f_1(1420)$ decaying into $K^*\overline{K}$, and for two pseudoscalars in the $\eta(1440)$ region, the $\eta(1405)$ and $\eta(1475)$, decaying into $a_0(980)\pi$ and $K^*\overline{K}$, respectively. Alternatively, these two structures could originate from a single pole. Doubts have been expressed on the existence of the $\eta(1295)$. The $f_1(1510)$ is not well established.

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