THE (1405), (1475), f1(1420), AND f1(1510) (Revised February 2010)

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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 $p\bar{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \rightarrow K\bar{K}\pi$ [1]. This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\bar{K}$ with roughly equal contributions. The $\eta(1440)$ was also observed in radiative $J/\psi(1S)$ decay into $K\bar{K}\pi$ [2–4] and $\gamma\rho$ [5]. There is now 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 $K\bar{K}\pi$) and the latter mainly to $K^*(892)\bar{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: $\pi^-p$ [6,7]; radiative $J/\psi(1S)$ decay [8,9]; and $p\bar{p}$ annihilation at rest [11–14]. All of them give values for the masses, widths, and decay modes in reasonable agreement. However, Ref. [9] favors a state decaying into $K^*(892)\bar{K}$ at a lower mass than the state decaying into $a_0(980)\pi$, although agreement with MARK-III is not excluded. In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\bar{K}\pi$ 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 $\eta\pi^+\pi^-$ [15], which reports a mass of 1400 MeV, in line with the existence of the $\eta(1405)$ decaying into $a_0(980)\pi$. BES [10] reports an enhancement in $K^+K^-\pi^0$ around 1.44 GeV in $J/\psi(1S)$ decay, recoiling against an $\omega$ (but not a $\phi$) 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).

The $\eta(1405)$ is also observed in $p\bar{p}$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$, where it decays into $\eta\pi\pi$ [16]. The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ signal, in agreement with MARK III [15] and DM2 [4].

The $\eta(1295)$ has been observed by four $\pi^-p$ experiments [7,17–19], and evidence is reported in $p\bar{p}$ annihilation [23–25]. 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 [20] reports evidence for a signal around 1295 MeV in $B$ decays into $\eta\pi\pi K$. 


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However, the existence of the $\eta(1295)$ is questioned in Refs. [21] and [22]. 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 $\bar{p}p \rightarrow 4\pi\eta$). The pseudoscalar signal around 1400 MeV is then attributed to the first radial excitation of the $\eta$.

Assuming establishment of the $\eta(1295)$, the $\eta(1475)$ could be the first radial excitation of the $\eta'$, with the $\eta(1295)$ being the first radial excitation of the $\eta$. Ideal mixing, suggested by the $\eta(1295)$ and $\pi(1300)$ mass degeneracy, would then imply that the second isoscalar in the nonet is mainly $s\bar{s}$, and hence couples to $K^*\bar{K}$, in agreement with properties of the $\eta(1475)$. Also, its width matches the expected width for the radially excited $s\bar{s}$ state [26,27]. A study of radial excitations of pseudoscalar mesons [28] 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 $K\bar{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions by L3 [29]. The analysis leads to a clear $\eta(1475)$ signal in $K\bar{K}\pi$, decaying into $K^*\bar{K}$, very well identified in the untagged data sample, where contamination from spin 1 resonances is not allowed. At the same time, L3 [29] did not observe the $\eta(1405)$, neither in $K\bar{K}\pi$ 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 [29] suggest that $\eta(1405)$ has a large gluonic content (see also Refs. [30] and [31]).

The L3 result is somewhat in disagreement with that of CLEO-II, which did not observe any pseudoscalar signal in $\gamma\gamma \rightarrow \eta(1475) \rightarrow K^0_SK^{\pm}\pi^\mp$ [32]. However, more data are required. Moreover, after the CLEO-II result, L3 performed a further analysis with full statistics [33], confirming the evidence of the $\eta(1475)$ observed by L3. The CLEO upper limit [32] for $\Gamma_{\gamma\gamma}(\eta(1475))$, and the L3 results [33], are consistent with the world average for the $\eta(1475)$ width.
BaBar [20] also reports the \( \eta(1475) \) in \( B \) decays into \( K\bar{K}\pi \) (and possibly \( \eta\pi\pi \)). Upper limits are given for \( \eta(1405) \) decay into \( K\bar{K}^* \). The data sample is not sufficient to identify a possible \( \eta(1405) \) contribution into \( \eta\pi\pi \).

The gluonium interpretation for the \( \eta(1405) \) is not favored by lattice gauge theories which predict the \( 0^{-+} \) state above 2 GeV [34]. However, the \( \eta(1405) \) is an excellent candidate for the \( 0^{-+} \) glueball in the fluxtube model [35]. 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. [36] 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. [37] and [38]). A detailed review of the experimental situation is available in Ref. [39].

Let us now deal with \( 1^{++} \) isoscalars. The \( f_1(1420) \), decaying into \( K^*\bar{K} \), was first reported in \( \pi^-p \) reactions at 4 GeV/c [40]. However, later analyses found that the 1400–1500 MeV region was far more complex [41–43]. A reanalysis of the MARK III data in radiative \( J/\psi(1S) \) decay into \( K\bar{K}\pi \) [8] shows the \( f_1(1420) \) decaying into \( K^*\bar{K} \). Also, a C=+1 state is observed in tagged \( \gamma\gamma \) collisions (e.g., Ref. [44]).

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 \( \eta(1295) \) [17,45], and at 100 GeV/c Ref. [18] 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 \( \bar{p}p \) 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. [12] reports \( f_1(1420) \) decaying into \( K^*\bar{K} \). The \( f_1(1420) \), decaying into \( K\bar{K}\pi \), 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 \( K^*\bar{K} \), while the \( \eta(1440) \) is absent [46,47]. The \( K_S K_S \pi^0 \) 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 [48].

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 [49], and at 11 GeV/c [50]. Evidence is also reported in $\pi^-p$ at 8 GeV/c, based on the phase motion of the $1^{++} K^*\overline{K}$ wave [43]. A somewhat broader $1^{++}$ signal is also observed in $J/\psi(1S)$ radiative decay into $\eta\pi^+\pi^-$ [51].

The absence of $f_1(1420)$ in $K^-p$ [50] 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 $\pi^-p$ [52], while two experiments do not observe the $f_1(1510)$ in $K^-p$ [52,53]. The latter is also not seen in radiative $J/\psi(1S)$ decay [8,9] and possibly [10], central collisions [47], or $\gamma\gamma$ collisions [54], although, surprisingly for an $s\overline{s}$ state, a signal is reported in $4\pi$ decays [55]. These facts lead to the conclusion that $f_1(1510)$ is not well established [56].

Assigning the $f_1(1420)$ to the $1^{++}$ nonet, one finds a nonet mixing angle of $\sim 50^\circ$ [56]. 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. [57] and [58], respectively, while Ref. [59] argued for a molecular state formed by the $\pi$ orbiting in a $P$-wave around an $S$-wave $K\overline{K}$ state.

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. The $f_1(1510)$ is not well established.

References