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 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 [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 $K^*(892)\bar{K}$ at a lower mass than the state decaying into $a_0(980)\pi$. In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\bar{K}\pi$ 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 $\eta\pi^+\pi^-$ [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 $\omega$ (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). On the other hand, BES observes $\eta(1405) \rightarrow \eta\pi\pi$ in $J/\psi(1S)$ decay, recoiling against an $\omega$ [16].

The $\eta(1405)$ is also observed in $\bar{p}p$ 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 $K^*(892)\bar{K}$. Based on the isospin violating decay $J/\psi(1S) \rightarrow \gamma3\pi$ observed by BES [19]
the splitting could also be due to a triangular singularity mixing \( \eta \pi \pi \) and \( K^*(892)K \) [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 \( \bar{p}p \) 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 \( \eta \).

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 \( s\pi \), and hence couples to \( K^0\bar{K} \), in agreement with properties of the \( \eta(1475) \). Also, its width matches the expected width for the radially excited \( s\bar{s} \) state [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 \( K\bar{K}\pi \) and \( \eta\pi\pi \) channels were studied in \( \gamma\gamma \) collisions by L3 [34]. The analysis led to a clear \( \eta(1475) \) signal in \( K\bar{K}\pi \), 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 [34] 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 [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 $K^*\bar{K}$, 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 $K\bar{K}\pi$ [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. 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 \( \bar{p}p \) 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. 11 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 [53,54]. The \( K^0_mK^0\pi^0 \) 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 \( K^*\bar{K} \), compete for the \( s\bar{s} \) assignment in the 1\(^{++}\) nonet. The \( f_1(1510) \) was seen in \( K^-p \rightarrow \Lambda K\bar{K}\pi \) at 4 GeV/c [56], and at 11 GeV/c [57]. Evidence is also reported in \( \pi^-p \) at 8 GeV/c, based on the phase motion of the 1\(^{++}\) \( K^*\bar{K} \) 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 \( s\bar{s} \) member of the 1\(^{++}\) nonet. However, the \( f_1(1420) \) was reported in \( K^-p \) but not in \( \pi^-p \) [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 \( s\bar{s} \) state, a signal is reported in \( 4\pi \) 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 \( \sim 50^\circ \) [64]. However, arguments favoring the \( f_1(1420) \) being a hybrid \( q\bar{q}g \) 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 \( \pi \) orbiting in a \( P \)-wave around an \( S \)-wave \( K\bar{K} \) 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.

References

21. Xia-Gang Wu et al., prD87,014023.