

## 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  $\bar{p}p$  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  $K^*(892)\bar{K}$  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  $J/\psi(1S) \rightarrow \gamma 3\pi$  observed by BES [19]

the splitting could also be due to a triangular singularity mixing  $\eta\pi\pi$  and  $K^*(892)\bar{K}$  [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  $\bar{p}p \rightarrow 4\pi\eta$ ). 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 [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  $K_S^0 K_S^0 \pi^0$  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  $K^*\bar{K}$ , and for two pseudoscalars in the  $\eta(1440)$  region, the  $\eta(1405)$  and  $\eta(1475)$ , decaying into  $a_0(980)\pi$  and  $K^*\bar{K}$ , 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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