# 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 $\eta(1440)\pi^+\pi^-$, $\eta(1440) \to K\overline{K}\pi$ (BAILLON 67). 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 to $K\overline{K}\pi$ (SCHARRE 80, EDWARDS 82E, AUGUSTIN 90). 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 $K\overline{K}\pi$) and the latter mainly to $K^*(892)\overline{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: $\pi^-p$ (RATH 89, ADAMS 01); radiative $J/\psi(1S)$ decay (BAI 90C, AUGUSTIN 92); $\overline{p}p$ annihilation at rest (BERTIN 95, BERTIN 97, CICALO 99, NICHITIU 02). All of them give values for the masses, widths and decay modes in reasonable agreement. However, AUGUSTIN 92 favors a state decaying into $K^*(892)\overline{K}$ 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 $K\overline{K}\pi$ 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 $\eta\pi^+\pi^-$ (BOLTON 92B) which report a mass of 1400 MeV, in line with the existence of the $\eta(1405)$ decaying to $a_0(980)\pi$. This state is also observed in $\overline{p}p$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$, where it decays into $\eta\pi\pi$ (AMSLER 95F). The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ signal, in agreement with MARK III (BOLTON 92B) and DM2 (AUGUSTIN 90).

The existence of the $\eta(1295)$ is questioned by KLEMPT 05. However, this state has been observed by four $\pi^-p$ experiments (ADAMS 01, FUKUI 91C, ALDE 97B, MANAK 00A) and evidence is also reported in $\overline{p}p$ annihilation (ABELE 98, ANISOVICH 01, AMSLER 04B). In $J/\psi$ radiative decay an $\eta(1295)$ signal is seen in the $0^{-+}$ $\eta\pi\pi$ wave of DM2 data (AUGUSTIN 92).

Assuming that the $\eta(1295)$ is established, 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 $s\overline{s}$ and hence couples to $K^*\overline{K}$, in agreement with the $\eta(1475)$. Also its width matches the expected width for the radially excited $s\overline{s}$ state (CLOSE 97, BARNES 97).

The $K\overline{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions (ACCIARRI 01G). The analysis leads to an $\eta(1475)$ signal in $K\overline{K}\pi$, but the $\eta(1405)$ is not observed in $K\overline{K}\pi$ nor in $\eta\pi\pi$. This result is somewhat in disagreement with CLEO-II which did not observe any pseudoscalar signal in $\gamma\gamma \rightarrow \eta(1475) \rightarrow K^0_S K^\pm \pi^\mp$ (AHOHE 05), but more data are required. Since gluonium production is presumably suppressed in $\gamma\gamma$ collisions, the ACCIARRI 01G results suggest that the $\eta(1405)$ has a large gluonic content (see also CLOSE 97B, LI 03C). The observation of the $\eta(1475)$ combined with the absence of an $\eta(1405)$ signal strengthens the two-resonances hypothesis.

The gluonium interpretation is not favored by lattice gauge theories which predict the $0^{-+}$ state above 2 GeV (BALI 93). However, the $\eta(1405)$ is an excellent candidate for the $0^{-+}$ glueball in the flux tube model (FADDEEV 04). In this model the $0^{++}$ $f_0(1500)$ glueball is also naturally related to a $0^{-+}$ glueball with mass degeneracy broken in QCD.

Let us now deal with $1^{++}$ isoscalars. The $f_1(1420)$, decaying to $K^*\overline{K}$, was first reported in $\pi^- p$ reactions at 4 GeV/$c$ (DIONISI 80). However, later analyses found that the 1400 –1500 MeV region was far more complex (CHUNG 85, REEVES 86, BIRMAN 88). A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay to $K\overline{K}\pi$ (BAI 90C) shows the $f_1(1420)$ decaying into $K^*\overline{K}$. Also, a C=+1 state is observed in tagged $\gamma\gamma$ collisions (*e.g.*, BEHREND 89).

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 $\eta(1295)$ and $\eta(1440)$ (ANDO 86, FUKUI 91C) and at 100 GeV/$c$ ALDE 97B report the $\eta(1295)$ and $\eta(1440)$ decaying to $\eta\pi^0\pi^0$, 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, BERTIN 97 report $f_1(1420)$ decaying to $K^*\overline{K}$.

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 (ARMSTRONG 89, BARBERIS 97C). 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 to $\eta\pi\pi$ around 1400 MeV and hence the $\eta\pi\pi$ mode of $f_1(1420)$ must be suppressed (ARMSTRONG 91B).

We now turn to the experimental evidence for the $f_1(1510)$. Two states, the $f_1(1420)$ and the $f_1(1510)$, decaying to $K^*\overline{K}$, 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/$c$ (GAVILLET 82) and at 11 GeV/$c$ (ASTON 88C). Evidence is also reported in $\pi^-p$ at 8 GeV/$c$, based on the phase motion of the $1^{++}$ $K^*\overline{K}$ wave (BIRMAN 88).

The absence of $f_1(1420)$ in $K^-p$ (ASTON 88C) argues against this state being the $s\overline{s}$ member of the $1^{++}$ nonet. However, the $f_1(1420)$ was reported in $K^-p$ but not in $\pi^-p$ (BITYUKOV 84) while two experiments do not observe the $f_1(1510)$ in $K^-p$ (BITYUKOV 84, KING 91). It is also not seen in radiative $J/\psi(1S)$ decay (BAI 90C, AUGUSTIN 92), central collisions (BARBERIS 97C), nor in $\gamma\gamma$ collisions (AIHARA 88C), although, surprisingly for an $s\overline{s}$ state, a signal is reported in $4\pi$ decays (BAUER 93B). These facts lead to the conclusion that the $f_1(1510)$ needs experimental confirmation (CLOSE 97D).

Assigning the $f_1(1420)$ to the $1^{++}$ nonet one finds a nonet mixing angle of $\sim 50^\circ$ (CLOSE 97D). However, arguments favoring the $f_1(1420)$ being a hybrid $q\overline{q}g$ meson or a four-quark state were put forward by ISHIDA 89 and by CALDWELL 90, respectively, while LONGACRE 90 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 to $K^*\overline{K}$, and for two pseudoscalars in the $\eta(1440)$ region, the $\eta(1405)$ and $\eta(1475)$, decaying to $a_0(980)\pi$ and $K^*\overline{K}$, respectively. The $f_1(1510)$ is not well established.