THE $\eta(1440)$, $f_1(1420)$, AND $f_1(1510)$

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The first observation of $\eta(1440)$ was made in $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \rightarrow K\overline{K}\pi$ (BAILLON 67). This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ has also been observed in radiative $J/\psi(1S)$ decay to $K\overline{K}\pi$ (SCHARRE 80, EDWARDS 82E, AUGUSTIN 90).

The $f_1(1420)$, decaying to $K^*\overline{K}$ was reported in π^-p reactions at 4 GeV/c (DIONISI 80). However, later analyses found that the 1400–1500 MeV region is far more complex. In π^-p experiments (CHUNG 85, REEVES 86, BIRMAN 88) reported 0^{-+} with a dominant $a_0(980)\pi$ contribution to $K\overline{K}\pi$. The π^-p data of RATH 89 at 21 GeV/c suggest the presence of two pseudoscalars decaying to $K\overline{K}\pi$, one around 1410 MeV decaying through $a_0(980)\pi$ and the other around 1470 MeV, decaying to $K^*\overline{K}$. A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay to $K\overline{K}\pi$ (BAI 90C) also claims the existence of two pseudoscalars in the 1400–1500 MeV range, the lower mass state decaying through $a_0(980)\pi$ and the higher mass state decaying via $K^*\overline{K}$. In addition, $f_1(1420)$ is observed to decay into $K^*\overline{K}$.

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 $\eta(1440)$ and $\eta(1295)$ (ANDO 86, FUKUI 91C) and at 100 GeV ALDE 97B report $\eta(1295)$ and $\eta(1440)$ decaying to $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ and no evidence for $f_1(1420)$.

An experiment in $\overline{p}p$ annihilation at rest into $K\overline{K}3\pi$ (BERTIN 95) reports two pseudoscalars with decay properties similar to BAI 90C, although the lower state shows, apart from $a_0(980)\pi$, a large contribution from the direct decay $\eta(1440) \rightarrow K\overline{K}\pi$. We note that the data from AUGUSTIN 92 also suggest two states but their intermediate states, $a_0(980)\pi$ and $K^*\overline{K}$, are reversed relative to BAI 90C.

In $J/\psi(1S)$ radiative decay $\eta(1440)$ decays to $K\overline{K}\pi$ through $a_0(980)\pi$ and hence a signal is also expected in the $\eta\pi\pi$ mass spectrum. This has indeed been observed by MARK III in

$\eta\pi^+\pi^-$ (BOLTON 92B) which report a mass of 1400 MeV, in line with the existence of a low mass pseudoscalar in the $\eta(1440)$ structure, 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 to $\eta\pi\pi$ (AMSLER 95F). The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ rate, in accord with MARK III (BOLTON 92B) and DM2 (AUGUSTIN 90). However, ALDE 97B reports only a very small contribution of $a_0(980)\pi$.

One of these two pseudoscalars could be the first radial excitation of the η', with $\eta(1295)$ the first radial 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 accord with observations for the upper $\eta(1440)$ state. This scheme then favors an exotic interpretation of the lower state, perhaps gluonium mixed with $q\overline{q}$ (CLOSE 97B) or a bound state of gluinos (FARRAR 96). The gluonium interpretation is, however, not favoured by lattice gauge theories, which predict the 0^{-+} state above 2 GeV (BALI 93).

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 $K^*\overline{K}$ in gaseous hydrogen, while confirming their earlier evidence for two pseudoscalars (BERTIN 95).

In $\gamma\gamma$ fusion from e^+e^- annihilations, a signal around 1420 MeV is seen in single-tag events (GIDAL 87B, AIHARA 88B, BEHREND 89, HILL 89) where one of the two photons is off-shell. However, it is totally absent in the untagged events where both photons are real. This points to a spin 1 object which is not produced by two real (massless) photons (Yang-Landau theorem). The 2γ decays also implies $C = +1$. For the parity, AIHARA 88C and BEHREND 89 both find angular distributions with positive parity preferred, but negative parity cannot be excluded.

The $f_1(1420)$ is definitively observed in $K\overline{K}\pi$ in pp central production at 300 and 450 GeV, together with $f_1(1285)$. The latter decays via $a_0(980)\pi$ and the former only via $K^*\overline{K}$, while

$\eta(1440)$ is absent (ARMSTRONG 89, BARBERIS 97C). The $K_S K_S \pi^0$ decay mode of $f_1(1420)$ establishes unambiguously that 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 $f_1(1420)$ is suppressed (ARMSTRONG 91B).

We now turn to the experimental evidence for $f_1(1510)$. Two states, $f_1(1420)$ and $f_1(1510)$, 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 $f_1(1420)$ being the $s\overline{s}$ member of the 1^{++} nonet. However, $f_1(1420)$ has been reported in $K^- p$ but not in $\pi^- p$ (BITYUKOV 84) while two experiments do not observe $f_1(1510)$ 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 and surprisingly for an $s\overline{s}$ state, a signal is reported in 4π decays (BAUER 93B). These facts led to the conclusion that $f_1(1510)$ is not well established and that its assignment as $s\overline{s}$ member of the 1^{++} nonet is premature (CLOSE 97D). The Particle Data Group agrees and has removed this state from the Summary Table. Assigning instead $f_1(1420)$ to the 1^{++} nonet one finds a nonet mixing angle of $\sim 50^\circ$ (CLOSE 97D). This is derived from the mass formula and from $f_1(1285)$ radiative decays to $\phi\gamma$ (BITYUKOV 88) and $\rho\gamma$ (AMELIN 95).

Arguments favoring $f_1(1420)$ being a hybrid $q\overline{q}g$ meson or a four-quark state are put forward by ISHIDA 89 and by CALDWELL 90, respectively, while LONGACRE 90 argues that this particle is a molecular state formed by the π orbiting in a P-wave around an S-wave $K\overline{K}$ state.

Summarizing, there is strong evidence for $f_1(1420)$, mostly produced in central collisions and decaying to $K^*\overline{K}$, and for $\eta(1440)$ mostly produced in radiative $J/\psi(1S)$ decay and $\overline{p}p$ annihilation at rest, decaying to $K^*\overline{K}$ and $a_0(980)\pi$. Confusion remains as to which states are observed in $\pi^- p$ interactions. The $f_1(1510)$ is not well established. Furthermore, there are experimental indications for the presence of two pseudoscalars in the $\eta(1440)$ structure. Accordingly, the Particle Data Group has split the $K\overline{K}\pi$ entry for $\eta(1440)$ into $a_0(980)\pi$ and $K^*\overline{K}$.