THE $\eta(1405)$, $\eta(1475)$, $f_1(1420)$, AND $f_1(1510)$

Revised December 2003 by M. Aguilar-Benitez (CIEMAT), C. Amsler (Zürich), and A. Masoni (INFN Cagliari).

A pseudoscalar meson decaying into $K\overline{K}\pi$ was first observed in the 1400–1500 mass region in $p\overline{p}$ annihilation at rest into $(K\overline{K}\pi)\pi^+\pi^-$ (BAILLON 67). This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. It was then observed in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ (SCHARRE 80, EDWARDS 82E, AUGUSTIN 90). This meson was previously called $\eta(1440)$. However, there is now evidence for the existence of two pseudoscalars in this mass region, and accordingly, we have split the $\eta(1440)$ into $\eta(1405)$ 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); and $\overline{p}p$ annihilation at rest (BERTIN 95,97, CICALO 99, NICHITIU 02). All of them give values for the masses, widths, and decay modes in reasonable agreement. However, AUGUSTIN 92 finds the state decaying into $K^*(892)\overline{K}$ at a lower mass than the state decaying into $a_0(980)\pi$.

In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\overline{K}\pi$ 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). 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 $\eta(1475)$ could be the first radial excitation of the η', with the $\eta(1295)$ being the first radial excitation 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 agreement with observation. Its width also matches the expected width for the radially excited $s\overline{s}$ state (CLOSE 97, BARNES 97).

An investigation of the $K\overline{K}\pi$ and $\eta\pi\pi$ channels in $\gamma\gamma$ collisions was performed (ACCIARRI 01G). They observed the $\eta(1475)$ in $K\overline{K}\pi$, but not the $\eta(1405)$ in $\eta\pi\pi$. Since gluonium production is presumably suppressed in $\gamma\gamma$ collisions, the ACCIARRI 01G results suggest that this latter state has a large gluonic content (CLOSE 97B, LI 03C). The gluonium interpretation, however, is not favored by lattice gauge theories, which predict the 0^{-+} state above 2 GeV (BALI 93).

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, ADAMS 01). 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 $\pi^- p \to \eta\pi\pi n$ charge-exchange reactions at 8–9 GeV/c, the $\eta\pi\pi$ mass spectrum is dominated by the $\eta(1405/1475)$, and $\eta(1295)$ (ANDO 86, FUKUI 91C), and at 100 GeV/c ALDE 97B report $\eta(1295)$ and $\eta(1405/1475)$ 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 the $f_1(1420)$ decaying into $K^*\overline{K}$.

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 no pseudoscalar is observed (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 into $\eta\pi\pi$ around 1400 MeV, and hence, the $\eta\pi\pi$ mode of the $f_1(1420)$ must be suppressed (ARMSTRONG 91B).

We now turn to the experimental evidence for the $f_1(1510)$. Two states, the $f_1(1420)$ and $f_1(1510)$, decaying to $K^*\overline{K}$, compete for the $s\overline{s}$ assignment in the 1^{++} nonet. The $f_1(1510)$ was seen in $K^- p \to \Lambda K\overline{K}\pi$ 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 the $f_1(1420)$ in $K^- p$ (ASTON 88C) argues against being the $s\overline{s}$ member of the 1^{++} nonet. However, the $f_1(1420)$ was indeed reported in $K^- p$, but not in $\pi^- p$ (BITYUKOV 84).

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), or in $\gamma\gamma$ collisions (AIHARA 88C), although, surprisingly for an $s\overline{s}$ state, a signal is reported in 4π decays (BAUER 93B). These facts leads to the conclusion that the $f_1(1510)$ is not well established (CLOSE 97D).

Assigning the $f_1(1420)$ to the 1^{++} nonet, one finds a nonet mixing angle of $\sim 50°$ (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 π 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 1400-1500 MeV 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.

References may be found at the end of the $\eta(1405)$, $\eta(1475)$ $f_1(1420)$, and $f_1(1510)$ Listings.