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

Written April 2000 by M. Aguilar-Benitez (CIEMAT, Madrid), C. Amsler (Zürich), and A. Masoni (INFN Cagliari).

The first observation of $\eta(1440)$ 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 $\eta(1440)$ 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 $\pi^-p \to \eta\pi\pi n$ 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/c, ALDE 97B reports $\eta(1295)$ and $\eta(1440)$ decaying to $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ signal, 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 $\eta(1440) \to K\overline{K}\pi$.

The result of BERTIN 95 was supported by further $\overline{p}p$ data from the same experiment (BERTIN 97, CICALO 99). In particular, the data of CICALO 99 provided a decisive evidence for the presence of two pseudoscalar states.

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.

Actually the interpretation of AUGUSTIN 92 is disfavored for several reasons: first, it disagrees with all the other $K\overline{K}3\pi$ results reporting two pseudoscalar states (they all agree in assigning the $K^*(892)\overline{K}$ decay mode to the higher mass pseudoscalar); second, it also disagrees with the $\eta\pi\pi$ results, because if the high mass pseudoscalar decays into $a_0(980)\pi$, then this state (and not the one at lower mass) should be seen in $\eta\pi\pi$ (see below).

In $J/\psi(1S)$ radiative decay, the $\eta(1440)$ 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 $\eta\pi\pi$ signal, in agreement with MARK III (BOLTON 92B) and DM2 (AUGUSTIN 90). However, ALDE 97B reports only a very small contribution due to $a_0(980)\pi$.

There is now a fairly consistent picture for the existence of two pseudoscalars. We call them η_L and η_H. The first one decays mainly through $a_0(980)\pi$ or direct $K\overline{K}\pi$. The second one decays mainly to $K^*(892)\overline{K}$. The η_L is seen both in $K\overline{K}\pi$ and $\eta\pi\pi$ experiments. The η_H is seen only in $K\overline{K}\pi$ experiments. The simultaneous observation of two pseudoscalars is reported in three production mechanisms by four different experiments: π^-p (RATH 89); radiative $J/\psi(1S)$ decay (BAI 90C, AUGUSTIN 92); and $\overline{p}p$ annihilation at rest (BERTIN 95, BERTIN 97, CICALO 99). All of them give values for the masses, widths and decay modes (with the exception of AUGUSTIN 92 quoted above) in reasonable agreement.

A recent paper reports only one pseudoscalar state seen in $J/\psi(1S)$ decay to $K\overline{K}\pi$ (BAI 98C), but its statistics are poorer, by a factor six, with respect to MARK III on the same final state (BAI 90C), and by more than an order of magnitude

with respect to $\overline{p}p$ data (BERTIN 95, BERTIN 97, CICALO 99). It is, therefore, not surprising that their analysis is not capable to discriminate between the two states.

One of these two pseudoscalars 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 observations for the upper $\eta(1440)$ state.

Also its width matches the expected width for the radially excited $\eta^{s\overline{s}}$ (CLOSE 97, BARNES 97).

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 favored 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 reports $f_1(1420)$ decaying to $K^*\overline{K}$, 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 decay 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 $f_1(1420)$, decaying in $K\overline{K}\pi$, is definitely seen in pp central production at 300 and 450 GeV/c, 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 $K_SK_S\pi^0$ decay mode of $f_1(1420)$ 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 $f_1(1420)$ 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 $K^-p \to \Lambda K\overline{K}\pi$ at 4 GeV/c (GAVILLET 82), and at 11 GeV/c (ASTON 88C). Evidence is also reported in π^-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 π^-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), 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 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 has removed this state from the Summary Table. Assigning, instead, the $f_1(1420)$ 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 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 rather convincing 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, and decaying to $K^*\overline{K}$ and $a_0(980)\pi$. Confusion remains as to which states are observed in π^-p interactions. The $f_1(1510)$ is not well established.

Furthermore, there are fairly strong experimental indications for the presence of two pseudoscalars in the $\eta(1440)$ structure

The available information has led the Particle Data Group to split the $K\overline{K}\pi$ entry for $\eta(1440)$ into $a_0(980)\pi$ and $K^*\overline{K}$.