

## THE PSEUDOSCALAR AND PSEUDOVECTOR MESONS IN THE 1400 MEV REGION

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This minireview deals with some of the  $0^{-+}$  and  $1^{++}$  mesons reported in the 1200–1500 MeV region, namely the  $\eta(1405)$ ,  $\eta(1475)$ ,  $f_1(1285)$   $f_1(1420)$ ,  $a_1(1420)$  and  $f_1(1510)$ . The first observation of a pseudoscalar resonance around 1400 MeV – 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 into  $a_0(980)\pi$  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]. However, two pseudoscalars are now reported 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 that are 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 reported a mass of 1400 MeV, in line with the existence of the  $\eta(1405)$  decaying into  $a_0(980)\pi$ .

BESII [15] observes 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, BESII observes  $\eta(1405) \rightarrow \eta\pi\pi$  in  $J/\psi(1S)$  decay, recoiling against an  $\omega$  [16]. A single unresolved broad peak is also observed by BESIII in the decay  $\psi(2S) \rightarrow \omega K^*K$  which could be due to  $\eta(1405)$ ,  $\eta(1475)$  and  $f_1(1420)$  [17].

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  $\eta\pi\pi$  [18]. 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. [19] 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 BESIII [20] the splitting could also be due to a triangular singularity mixing  $\eta\pi\pi$  and  $K^*(892)\bar{K}$  [21–22]. However, in a further paper [23], using the approach of [21], the authors concluded that the BESIII results can be reproduced either with the  $\eta(1405)$  or the  $\eta(1475)$ , or by a mixture of these two states.

The  $\eta(1295)$  has been observed by four  $\pi^-p$  experiments [7,24–26], and evidence is reported in  $\bar{p}p$  annihilation [27–29]. In  $J/\psi(1S)$  radiative decay, the  $\eta(1295)$  signal is evident in the  $0^{-+}$   $\eta\pi\pi$  wave of the DM2 data [9]. Also BaBar [30] reports evidence for a signal around 1295 MeV in  $B$  decays into  $\eta\pi\pi K$ . Nonetheless, the existence of the  $\eta(1295)$  is questioned in Refs. [19] and [31] in which the authors claim the existence of a single pseudoscalar meson at 1440 MeV, the first radial excitation of the  $\eta$ . This conclusion is mainly based on the analysis of the annihilation  $\bar{p}p \rightarrow 4\pi\eta$  with Crystal Barrel data [32].

Considering that the  $\eta(1295)$  has been reported by several experiments, using different production mechanisms, we shall assume that this state is established. The  $\eta(1475)$  could then 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 [33,34]. A study of radial excitations of pseudoscalar mesons [35] 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 [36]. 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 [36] 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 [36] suggest that  $\eta(1405)$  has a large gluonic content (see also Refs. [37] and [38]).

The L3 result is somewhat in disagreement with that of CLEO-II, which did not observe any pseudoscalar signal in  $\gamma\gamma \rightarrow \eta(1475) \rightarrow K_S^0 K^\pm \pi^\mp$  [39]. However, more data are required. Moreover, after the CLEO-II result, L3 performed a further analysis with full statistics [40], confirming their previous evidence for the  $\eta(1475)$ . The CLEO upper limit [39] for  $\Gamma_{\gamma\gamma}(\eta(1475))$ , and the L3 results [40], are consistent with the world average for the  $\eta(1475)$  width.

BaBar [30] 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  $f_1(1285)$ ) 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 [41,42] (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 [43]. 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. [44] 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. [45–47]. A detailed review of the experimental situation is available in Ref. [48].

Let us now deal with the  $1^{++}$  mesons. The pseudovector nonet is believed to consist of the isovector  $a_1(1260)$ , the

isoscalsars  $f_1(1285)$  and  $f_1(1420)$ , and the  $K_{1A}$ , which is a mixture of about 50%  $K_1(1270)$  and 50%  $K_1(1400)$ . (This last property prevents a straightforward calculation of the nonet mixing angle via the mass formulae.) The  $f_1(1285)$  could also be a  $K^*\bar{K}$  molecule [49] or as a tetraquark state [50] and the  $f_1(1420)$  a  $K^*\bar{K}$  molecule, due to the proximity of the  $K^*\bar{K}$  threshold [51]. LHCb has analyzed the decays  $\bar{B}^0$  and  $\bar{B}_s^0 \rightarrow J/\psi(1S)f_1(1285)$  and determined the nonet mixing angle to be consistent with a mostly  $u\bar{u} + d\bar{d}$  structure [52] without specifying the identity of its isoscalar partner. This is consistent with earlier determinations assuming the  $f_1(1420)$  as the isoscalar partner [53] and the ratio of  $\bar{B}^0/\bar{B}_s^0$  decay rates excludes the tetraquark interpretation of this state [52].

The  $f_1(1420)$ , decaying into  $K^*\bar{K}$ , was first reported in  $\pi^-p$  reactions at 4 GeV/c [54]. However, later analyses found that the 1400–1500 MeV region was far more complex [55–57]. 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  $K^*\bar{K}$ . A  $C=+1$  state is also seen in tagged  $\gamma\gamma$  collisions (*e.g.*, Ref. [58]).

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  $\eta(1295)$  [24,59], and at 100 GeV/c Ref. [25] 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 [60,61]. 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 [62].

The COMPASS Collaboration has recently reported an isovector state at 1414 MeV, the  $a_1(1420)$  [63]. This relatively

narrow state ( $\simeq 150$  MeV) is produced by diffractive dissociation with 190 GeV pions in  $\pi N \rightarrow 3\pi N$ , decays into  $f_0(980)\pi \rightarrow 3\pi$  (P-wave) and has therefore the quantum numbers  $(I^G)J^{PC} = (1^-)1^{++}$ . The pseudovector nonet already contains the established  $a_1(1260)$  as the  $I = 1$  state. As mentioned above, the  $f_1(1420)$  has been interpreted as a  $K^*\bar{K}$  molecule [51]. The new  $a_1(1420)$  could be its isovector partner. Arguments favoring the  $f_1(1420)$  being a hybrid  $q\bar{q}g$  meson [64] or a four-quark state [65] were also put forward. The  $q\bar{q}$  state would then remain to be identified, with the  $f_1(1510)$  (see below) as a candidate. However, an alternative explanation is suggested in Ref. [66] in which the authors claim a single  $1^{++}$  isovector around 1400 MeV, leading to two peaks in the  $3\pi$  mass spectrum, depending on the production mechanism,  $\rho\pi$  for the  $a_1(1260)$  and  $f_0(980)\pi$  for the  $a_1(1420)$ .

We now turn to the experimental evidence for the  $f_1(1510)$ . The  $f_1(1510)$  was seen in  $K^-p \rightarrow \Lambda K\bar{K}\pi$  at 4 GeV/c [67], and at 11 GeV/c [68]. Evidence is also reported in  $\pi^-p$  at 8 GeV/c, based on the phase motion of the  $1^{++}$   $K^*\bar{K}$  wave [57]. A somewhat broader  $1^{++}$  signal is also observed in  $J/\psi(1S) \rightarrow \gamma\eta\pi^+\pi^-$  [69] as well as a small signal in  $J/\psi(1S) \rightarrow \gamma\eta'\pi^+\pi^-$ , attributed to the  $f_1(1510)$  [70].

The absence of  $f_1(1420)$  in  $K^-p$  [68] 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  $\pi^-p$  [71], while two experiments do not observe the  $f_1(1510)$  in  $K^-p$  [71,72]. The latter is also not seen in central collisions [61], nor  $\gamma\gamma$  collisions [73], although, surprisingly for an  $s\bar{s}$  state, a signal is reported in  $4\pi$  decays [74]. These facts led to the conclusion that  $f_1(1510)$  was not well established [75].

Summarizing, there is evidence for two isovector  $1^{++}$  states in the 1400 MeV region, the  $a_1(1260)$  and  $a_1(1420)$ , which cannot be both  $q\bar{q}$  states. These two states could stem from the same pole, or the latter be exotic (tetraquark or hybrid) or a molecular state. The  $f_1(1285)$  and the  $f_1(1420)$  are well known but their nature ( $q\bar{q}$ , tetraquark or molecular) remains to be established. In the  $0^{-+}$  sector there is evidence for two pseudoscalars in the 1400 MeV 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  $f_1(1510)$  remains to be firmly established.

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