# 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 $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \rightarrow K\overline{K}\pi$ [1]. This state was reported to decay into $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ was also observed in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [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 $K\overline{K}\pi$) and the latter mainly to $K^*(892)\overline{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: $\pi^- p$ [6,7]; radiative $J/\psi(1S)$ decay [8,9]; and $\overline{p}p$ 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 $K^*(892)\overline{K}$ 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 $\eta\pi^+\pi^-$ [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 $\overline{p}p$ 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 $K^*(892)\overline{K}$. Based on the isospin violating decay $J/\psi(1S) \to \gamma\, 3\pi$ observed by BESIII [20] the splitting could also be due to a triangular singularity mixing $\eta\pi\pi$ and $K^*(892)\overline{K}$ [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 $\overline{p}p$ 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 $\bar{p}p \to 4\pi\eta$ with Crystal Barrel data [32].

Considering that the $\eta(1295)$ has been reported by several experiments, using different production mechnisms, 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 $s\overline{s}$, and hence couples to $K^*\overline{K}$, in agreement with properties of the $\eta(1475)$. Also, its width matches the expected width for the radially excited $s\overline{s}$ 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 $s\overline{s}$ admixture also in the $\eta(1405)$.

The $K\overline{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions by L3 [36]. The analysis led to a clear $\eta(1475)$ signal in $K\overline{K}\pi$, decaying into $K^*\overline{K}$, 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 $K\overline{K}\pi$ 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 $\gamma\gamma \rightarrow \eta(1475) \rightarrow K^0_S K^\pm \pi^\mp$ [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 isoscalars $f_1(1285)$ 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 $K^*\overline{K}$ molecule [49] or as a tetraquark state [50] and the $f_1(1420)$ a $K^*\overline{K}$ molecule, due to the proximity of the $K^*\overline{K}$ threshold [51]. LHCb has analyzed the decays $\overline{B}^0$ and $\overline{B}^0_s \to J/\psi(1S) f_1(1285)$ and determined the nonet mixing angle to be consistent with a mostly $u\overline{u} + d\overline{d}$ 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 $\overline{B}^0/\overline{B}^0_s$ decay rates excludes the tetraquark interpretation of this state [52].

The $f_1(1420)$, decaying into $K^*\overline{K}$, 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 $K\overline{K}\pi$ [8] shows the $f_1(1420)$ decaying into $K^*\overline{K}$. A C=+1 state is also seen in tagged $\gamma\gamma$ collisions (*e.g.*, Ref. [58]) .

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 $\eta(1440)$ 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 $\overline{p}p$ annihilation at rest in liquid hydrogen, which proceeds dominantly through $S$-wave annihilation. However, in gaseous hydrogen, $P$-wave annihilation is enhanced and, indeed, Ref. [11] reports $f_1(1420)$ 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 the $\eta(1440)$ is absent [60,61]. The $K^0_S K^0_S \pi^0$ 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 [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 $K^*\overline{K}$ molecule [51]. The new $a_1(1420)$ could be its isovector partner. Arguments favoring the $f_1(1420)$ being a hybrid $q\overline{q}g$ meson [64] or a four-quark state [65] were also put forward. The $q\overline{q}$ 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 $K^-p \rightarrow \Lambda K\overline{K}\pi$ 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 $1^{++}$ $K^*\overline{K}$ 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 $s\overline{s}$ 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 $s\overline{s}$ 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 $q\overline{q}$ 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 ($q\overline{q}$, 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 $K^*\overline{K}$, 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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