63. 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 $\eta(1295)$, $\eta(1405)$, $\eta(1475)$, $f_1(1285)$ $f_1(1420)$, $a_1(1420)$ 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 $\eta(1440)\pi^+\pi^-$, $\eta(1440) \to K\overline{K}\pi$ [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] and was in the eighties considered as a glueball candidate

However, two pseudoscalars are now observed 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: π^-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 ω (but not a ϕ) 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 $\eta(1405) \to \eta\pi\pi$ in $J/\psi(1S)$ decay, recoiling against an ω [16]. A single unresolved broad peak is also observed by BESIII in the decay $\psi(2S) \to \omega K^*K$ 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].

Whether one or two pseudoscalar mesons exist in this mass region is still an open issue. According to Ref. [19] the splitting of a single state is 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]. In a further paper [23], using the approach of [21], the authors conclude 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 π^-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 also claim the existence of a single pseudoscalar meson at 1440 MeV, the first radial excitation of the η. This conclusion is mainly based on a PhD thesis of the annihilation channel $\bar{p}p \to 4\pi\eta$ with Crystal Barrel data [32].

Since the $\eta(1295)$ has been reported by several experiments, using different production mechanisms, let us assume this state to be established. The $\eta(1475)$ could then 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 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 $K\overline{K}\pi$ 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.

Under the assumption that two pseudoscalars exist in the 1400 MeV region, the $\eta(1405)$ could be a glueball, but this 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 superposition with mixing angle $\sim 34°$ of $K_1(1270)$ and $K_1(1400)$ [49]. The $f_1(1285)$ could also be a $K^*\overline{K}$ molecule [50] or as a tetraquark state [51] and the $f_1(1420)$ a $K^*\overline{K}$ molecule, due to the proximity of the $K^*\overline{K}$ threshold [52]. LHCb has analyzed the decays $\overline{B}^0$ and $\overline{B}^0_s \rightarrow J/\psi(1S) f_1(1285)$ and determined the nonet mixing angle to be consistent with a mostly $u\overline{u} + d\overline{d}$ structure [53] without specifying the identity of its isoscalar partner. This is consistent with earlier determinations assuming the $f_1(1420)$ as the isoscalar partner [54] and the ratio of $\overline{B}^0/\overline{B}^0_s$ decay rates excludes the tetraquark interpretation of this state [53].

The $f_1(1420)$, decaying into $K^*\overline{K}$, was first reported in $\pi^- p$ reactions at 4 GeV/c [55]. However, later analyses found that the 1400–1500 MeV region was far more complex [56–58]. 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. [59]).

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, 60], 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 [61, 62]. 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 [63].

The COMPASS Collaboration has recently reported an isovector state at 1411 MeV, the $a_1(1420)$ [64] [65]. This relatively narrow state (161 MeV) is produced by diffractive dissociation with 190 GeV pions in $\pi N \to 3\pi N$, decays into $f_0(980)\pi \to 3\pi$ (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 [52]. The new $a_1(1420)$ could be its isovector partner. Arguments favoring the $f_1(1420)$ being a hybrid $q\bar{q}g$ meson [66] or a four-quark state [67] 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, alternative explanations are suggested: A single 1^{++} isovector around 1400 MeV, can lead to two peaks in the 3π mass spectrum, depending on the production mechanism, $\rho\pi$ [68] or $K^*\overline{K} \to K\overline{K}\pi \to f_0(980)\pi$ [69] for the $a_1(1260)$ and $f_0(980)\pi$ for the $a_1(1420)$.

A similar mechanism is invoked for the $f_1(1420)$, which is claimed to result from the $K^*\overline{K}$ and $a_0(980)\pi$ decay modes of the $f_1(1285)$ [70]. The absence of $f_1(1420)$ in K^-p [71] indeed 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 π^-p [72], while two experiments do not observe the $f_1(1510)$ in K^-p [72, 73]. The latter is also not seen in central collisions [62], nor $\gamma\gamma$ collisions [74], although, surprisingly for an $s\bar{s}$ state, a signal is reported in 4π decays [75].

We now turn to the experimental evidence for the $f_1(1510)$ which competes with the $f_1(1420)$ to be the $s\bar{s}$ 1^{++} meson. The $f_1(1510)$ was seen in $K^-p \to \Lambda K\overline{K}\pi$ at 4 GeV/c [76], and at 11 GeV/c [71]. Evidence is also reported in π^-p at 8 GeV/c, based on the phase motion of the 1^{++} $K^*\overline{K}$ wave [58]. A somewhat broader 1^{++} signal is also observed in $J/\psi(1S) \to \gamma\eta\pi^+\pi^-$ [77] as well as a small signal in $J/\psi(1S) \to \gamma\eta'\pi^+\pi^-$, attributed to the $f_1(1510)$ [78]. The $f_1(1510)$ is not well established [79].

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 $K^*\overline{K}$, respectively. 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.

References

[1] P. H. Baillon *et al.*, Nuovo Cim. **A50**, 393 (1967).

[2] D. L. Scharre *et al.*, Phys. Lett. **97B**, 329 (1980).

[3] C. Edwards *et al.*, Phys. Rev. Lett. **49**, 259 (1982), [Erratum: Phys. Rev. Lett.50,219(1983)].

[4] J. E. Augustin *et al.* (DM2), Phys. Rev. **D42**, 10 (1990).

[5] J. Z. Bai *et al.* (BES), Phys. Lett. **B594**, 47 (2004), [hep-ex/0403008].

[6] M. G. Rath *et al.*, Phys. Rev. **D40**, 693 (1989).

[7] G. S. Adams *et al.* (E852), Phys. Lett. **B516**, 264 (2001), [hep-ex/0107042].

[8] Z. Bai *et al.* (MARK-III), Phys. Rev. Lett. **65**, 2507 (1990).

[9] J. E. Augustin *et al.* (DM2), Phys. Rev. **D46**, 1951 (1992).
[10] A. Bertin *et al.* (OBELIX), Phys. Lett. **B361**, 187 (1995).
[11] A. Bertin *et al.* (OBELIX), Phys. Lett. **B400**, 226 (1997).
[12] C. Cicalo *et al.* (OBELIX), Phys. Lett. **B462**, 453 (1999).
[13] F. Nichitiu *et al.* (OBELIX), Phys. Lett. **B545**, 261 (2002).
[14] T. Bolton *et al.*, Phys. Rev. Lett. **69**, 1328 (1992).
[15] M. Ablikim *et al.* (BES), Phys. Rev. **D77**, 032005 (2008), [arXiv:0712.1411].
[16] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **107**, 182001 (2011), [arXiv:1107.1806].
[17] M. Ablikim *et al.* (BESIII), Phys. Rev. **D87**, 092006 (2013), [arXiv:1303.6360].
[18] C. Amsler *et al.* (Crystal Barrel), Phys. Lett. **B358**, 389 (1995).
[19] E. Klempt and A. Zaitsev, Phys. Rept. **454**, 1 (2007), [arXiv:0708.4016].
[20] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **108**, 182001 (2012), [arXiv:1201.2737].
[21] J.-J. Wu *et al.*, Phys. Rev. Lett. **108**, 081803 (2012), [arXiv:1108.3772].
[22] X.-G. Wu *et al.*, Phys. Rev. **D87**, 1, 014023 (2013), [arXiv:1211.2148].
[23] F. Aceti *et al.*, Phys. Rev. **D86**, 114007 (2012), [arXiv:1209.6507].
[24] S. Fukui *et al.*, Phys. Lett. **B267**, 293 (1991), [,293(1991)].
[25] D. Alde *et al.* (GAMS), Phys. Atom. Nucl. **60**, 386 (1997), [Yad. Fiz.60,458(1997)].
[26] J. J. Manak *et al.* (E852), Phys. Rev. **D62**, 012003 (2000), [hep-ex/0001051].
[27] A. V. Anisovich *et al.*, Nucl. Phys. **A690**, 567 (2001).
[28] A. Abele *et al.*, Phys. Rev. **D57**, 3860 (1998).
[29] C. Amsler *et al.*, Eur. Phys. J. **C33**, 23 (2004).
[30] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **101**, 091801 (2008), [arXiv:0804.0411].
[31] E. Klempt, Int. J. Mod. Phys. **A21**, 739 (2006).
[32] J. Reinnarth, PhD Thesis, University of Bonn (2003), unpublished.
[33] F. E. Close and A. Kirk, Phys. Lett. **B397**, 333 (1997), [hep-ph/9701222].
[34] T. Barnes *et al.*, Phys. Rev. **D55**, 4157 (1997), [hep-ph/9609339].
[35] T. Gutsche, V. E. Lyubovitskij and M. C. Tichy, Phys. Rev. **D79**, 014036 (2009), [arXiv:0811.0668].
[36] M. Acciarri *et al.* (L3), Phys. Lett. **B501**, 1 (2001), [hep-ex/0011035].
[37] F. E. Close, G. R. Farrar and Z.-p. Li, Phys. Rev. **D55**, 5749 (1997), [hep-ph/9610280].
[38] D. M. Li, H. Yu and S. S. Fang, Eur. Phys. J. **C28**, 335 (2003).
[39] R. Ahohe *et al.* (CLEO), Phys. Rev. **D71**, 072001 (2005), [hep-ex/0501026].
[40] P. Achard *et al.* (L3), JHEP **03**, 018 (2007).
[41] G. S. Bali *et al.* (UKQCD), Phys. Lett. **B309**, 378 (1993), [hep-lat/9304012].
[42] C. J. Morningstar and M. J. Peardon, Phys. Rev. **D60**, 034509 (1999), [hep-lat/9901004].
[43] L. Faddeev, A. J. Niemi and U. Wiedner, Phys. Rev. **D70**, 114033 (2004), [hep-ph/0308240].
[44] H.-Y. Cheng, H.-n. Li and K.-F. Liu, Phys. Rev. **D79**, 014024 (2009), [arXiv:0811.2577].
[45] G. Li, Q. Zhao and C.-H. Chang, J. Phys. **G35**, 055002 (2008), [hep-ph/0701020].
[46] T. Gutsche, V. E. Lyubovitskij and M. C. Tichy, Phys. Rev. **D80**, 014014 (2009), [arXiv:0904.3414].

[47] B. A. Li, Phys. Rev. **D81**, 114002 (2010), [arXiv:0912.2323].
[48] A. Masoni, C. Cicalo and G. L. Usai, J. Phys. **G32**, R293 (2006).
[49] H.-Y. Cheng, Phys. Lett. **B707**, 116 (2012), [arXiv:1110.2249].
[50] F. Aceti, J.-J. Xie and E. Oset, Phys. Lett. **B750**, 609 (2015), [arXiv:1505.06134].
[51] S. Stone and L. Zhang, Phys. Rev. Lett. **111**, 6, 062001 (2013), [arXiv:1305.6554].
[52] R. S. Longacre, Phys. Rev. **D42**, 874 (1990).
[53] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **112**, 9, 091802 (2014), [arXiv:1310.2145].
[54] G. Gidal *et al.*, Phys. Rev. Lett. **59**, 2012 (1987).
[55] C. Dionisi *et al.* (CERN-College de France-Madrid-Stockholm), Nucl. Phys. **B169**, 1 (1980).
[56] S. U. Chung *et al.*, Phys. Rev. Lett. **55**, 779 (1985), [Erratum: Phys. Rev. Lett.55,2093(1985)].
[57] D. F. Reeves *et al.*, Phys. Rev. **D34**, 1960 (1986).
[58] A. Birman *et al.*, Phys. Rev. Lett. **61**, 1557 (1988), [Erratum: Phys. Rev. Lett.62,1577(1989)].
[59] H. J. Behrend *et al.* (CELLO), Z. Phys. **C42**, 367 (1989).
[60] A. Ando *et al.*, Phys. Rev. Lett. **57**, 1296 (1986).
[61] T. A. Armstrong *et al.* (WA76), Phys. Lett. **B221**, 216 (1989).
[62] D. Barberis *et al.* (WA102), Phys. Lett. **B413**, 225 (1997), [hep-ex/9707022].
[63] T. A. Armstrong *et al.* (WA76, Athens-Bari-Birmingham-CERN-College de France), Z. Phys. **C52**, 389 (1991).
[64] C. Adolph *et al.* (COMPASS), Phys. Rev. Lett. **115**, 8, 082001 (2015), [arXiv:1501.05732].
[65] M. Aghasyan *et al.* (COMPASS), Phys. Rev. **D98**, 9, 092003 (2018), [arXiv:1802.05913].
[66] S. Ishida *et al.*, Prog. Theor. Phys. **82**, 119 (1989).
[67] D.O. Caldwell, *Hadron 89 Conf., Ajaccio, Corsica*, p. 127.
[68] J.-L. Basdevant and E. L. Berger, Phys. Rev. Lett. **114**, 19, 192001 (2015), [arXiv:1504.05955].
[69] M. Mikhasenko, B. Ketzer and A. Sarantsev, Phys. Rev. **D91**, 9, 094015 (2015), [arXiv:1501.07023].
[70] V. R. Debastiani *et al.*, Phys. Rev. **D95**, 3, 034015 (2017), [arXiv:1611.05383].
[71] D. Aston *et al.*, Phys. Lett. **B201**, 573 (1988).
[72] P. F. Ermolov *et al.*, Sov. J. Nucl. Phys. **39**, 738 (1984), [Yad. Fiz.39,1170(1984)].
[73] J. Dowd *et al.*, Nucl. Phys. Proc. Suppl. **21**, 11 (1991).
[74] H. Aihara *et al.* (TPC/Two Gamma), Phys. Rev. **D38**, 1 (1988).
[75] D. A. Bauer *et al.* (TPC/Two Gamma), Phys. Rev. **D48**, 3976 (1993).
[76] P. Gavillet *et al.*, Z. Phys. **C16**, 119 (1982).
[77] J. Z. Bai *et al.* (BES), Phys. Lett. **B446**, 356 (1999).
[78] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **106**, 072002 (2011), [arXiv:1012.3510].
[79] F. E. Close and A. Kirk, Z. Phys. **C76**, 469 (1997), [hep-ph/9706543].