THE GLUEBALL CANDIDATE $\eta(1440)$ AS η RADIAL EXCITATION

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Abstract
The Particle Data Group decided to split the $\eta(1440)$ into two states, called η_L and η_H. The $\eta(1295)$ and the η_H are supposed to be the radial excitations of the η and η', respectively. The η_L state cannot be accomodated in a quark model; it cannot be a $q\bar{q}$ state, however, it might be a glueball. In this contribution it is shown that that the $\eta(1295)$ does not have the properties which must be expected for a radially excited state. The splitting of the $\eta(1440)$ is traced to a node in the wave function of a radial excitation. Hence the two peaks, η_L and η_H, originate from one resonance which is interpreted here as first radial excitation of the η.

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1 Short history of the $\eta(1440)$

The E/ι was discovered in 1967 in $p\bar{p}$ annihilation at rest into $(K\bar{K}\pi)\pi^+\pi^-$. It was the first meson found in a European experiment and was called E-meson [1]. Mass and width were determined to be $M = 1425 \pm 7, \Gamma = 80 \pm 10\,\mathrm{MeV}$, with quantum numbers $J^{PC} = 0^{-+}$. In the charge exchange reaction $\pi^- p \to n\mathrm{K}\bar{\mathrm{K}}\pi$, using a 1.5 to 4.2 GeV/c pion beam [2], a state was observed with $M = 1420 \pm 20, \Gamma = 60 \pm 20\,\mathrm{MeV}$ and $J^{PC} = 1^{++}$. Even though the quantum numbers were different, it was still called E-meson.

In 1979 there was a claim [3] for the $\eta(1295)$ which was later confirmed in other experiments. In 1980 the E–meson was observed [4] in radiative J/ψ decays into $(K\bar{K}\pi)$ with $M = 1440 \pm 20, \Gamma = 50 \pm 30\,\mathrm{MeV}$; the quantum numbers were 'rediscovered' [5] to be $J^{PC} = 0^{-+}$. The E–meson was renamed $\iota(1440)$ to underline the claim that it was the ι^{st} glueball discovered in an experiment. The $\iota(1440)$ is a very strong signal, one of the strongest, in radiative J/ψ decays. The radial excitation $\eta(1295)$ is not seen in this reaction; hence the $\iota(1440)$ must have a different nature. At that time it was proposed (and often still is) to be a glueball. Further studies, in particular by the Obelix collaboration at LEAR [7], showed that the $\iota(1440)$ is split into two components, a $\eta_L \to a_0(980)\pi$ with $M = 1405 \pm 5, \Gamma = 56 \pm 6\,\mathrm{MeV}$ and a $\eta_H \to \mathrm{K}^*\bar{\mathrm{K}} + \bar{\mathrm{K}}^*\mathrm{K}$ with $M = 1475 \pm 5, \Gamma = 81 \pm 11\,\mathrm{MeV}$: there seem to be 3 η states in the mass range from 1280 to 1480 MeV.

The $\eta(1295)$ is then likely the radial excitation of the η. It is mass degenerate with the $\pi(1300)$, hence the pseudoscalar radial excitations seem to be ideally mixed. Then, the $\bar{s}s$ partner should have a 240 MeV higher mass. The η_H could play this role. The η_L does not find η_L a slot in the spectrum of $\bar{q}q$ mesons; the low mass part of the $\iota(1440)$ could be a glueball. This conjecture is consistent with the observed decays. A pure flavor octet $\eta(xxx)$ state decays into K*K but not into $a_0(980)\pi$. In turn, a pure flavor singlet $\eta(xxx)$ state decays into $a_0(980)\pi$ but not into K*K. The η_H, with a large coupling to K*K, cannot possibly be a glueball, whereas the η_L with its $a_0(980)\pi$ decay mode can be.

The PDG 2004 supports this interpretation of the pseudoscalar mesons [8]:

π	η		η'	K
$\pi(1300)$	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$K(1460)$
$n\bar{n}$	$n\bar{n}$	glueball	$s\bar{s}$	$n\bar{s}$

Two quantitative tests have been proposed to test if a particular meson is glueball–like: the stickiness and the gluiness. The stickiness of a resonance R with mass $m_{\rm R}$ and two–photon width $\Gamma_{{\rm R}\to\gamma\gamma}$ is defined as:

$$S_{\rm R} = N_l \left(\frac{m_{\rm R}}{K_{{\rm J}\to\gamma{\rm R}}}\right)^{2l+1} \frac{\Gamma_{{\rm J}\to\gamma{\rm R}}}{\Gamma_{{\rm R}\to\gamma\gamma}} \ ,$$

where $K_{{\rm J}\to\gamma{\rm R}}$ is the energy of the photon in the J rest frame, l is the orbital angular momentum of the two initial photons or gluons ($l=1$ for 0^-), $\Gamma_{{\rm J}\to\gamma{\rm R}}$ is the J radiative decay width for R, and N_l is a normalization factor chosen to give $S_\eta = 1$. The L3 collaboration determined [9] this parameter to be $S_{\eta(1440)} = 79 \pm 26$.

The gluiness (G) was introduced [10,11] to quantify the ratio of the two–gluon and two–photon coupling of a particle and is defined as:

$$G = \frac{9\,e_q^4}{2} \left(\frac{\alpha}{\alpha_s}\right)^2 \frac{\Gamma_{{\rm R}\to{\rm gg}}}{\Gamma_{{\rm R}\to\gamma\gamma}} \ ,$$

where e_q is the relevant quark charge. $\Gamma_{{\rm R}\to{\rm gg}}$ is the two–gluon width of the resonance R, calculated from equation (3.4) of ref. [10]. Stickiness is a relative measure, gluiness is a normalised quantity and is expected to be near unity for a $q\bar{q}$ meson. The L3 collaboration determined [9] this quantity, $G_{\eta(1440)} = 41 \pm 14$.

These numbers can be compared to those for the η' for which $S_{\eta'} = 3.6 \pm 0.3$ and $G_{\eta'} = 5.2 \pm 0.8$ is determined, for $\alpha_s(958 MeV) = 0.56 \pm 0.07$. Also η' is 'gluish', but much more the η_L. The η_L is the first glueball!

2 The $\eta(1295)$ and the $\eta(1440)$ in radiative J/ψ decays

Radiative J/ψ decays show an asymmetric peak in the $\eta(1440)$ region therefore both the η_L and the η_H, must contribute to the process. Obvoiusly, radial excitations are produced in radiative J/ψ decays (not only glueballs). The $\eta(1295)$ must therefore also be produced, but it is not - at least not with the expected yield. Is there evidence for this state in other reactions?

At BES, $\eta(1295)$ and $\eta(1440)$ were studied in J/$\psi \to (\rho\gamma)\gamma$ and $\to (\phi\gamma)\gamma$ [12]. The $\eta(1440)$ (seen at 1424 MeV) is seen to decay strongly into $\rho\gamma$ and not into $\phi\gamma$. This is not consistent with the hypothesis of $\eta(1475)$ being a $s\bar{s}$ state. A peak below 1300 MeV is assigned to the $f_1(1285)$ even though a small contribution from $\eta(1295)$ cannot be excluded.

3 The $\eta(1295)$ and the $\eta(1440)$ in $\gamma\gamma$ at LEP

Photons couple to charges; in $\gamma\gamma$ fusion a radial excitation is hence expected to be produced more frequently than a glueball. In $\gamma\gamma$ fusion, both electron and positron scatter by emitting a photon. If the momentum transfer to the photons is small, the e^+ and e^- are scattered into forward angles (passing undetected through the beam pipe), thus the two photons are nearly real. If the e^+ or e^- has a large momentum transfer, the photon acquires mass, and we call the process $\gamma\gamma^*$ collision. Two massless photons couple to the $\eta(1295)$ but not to the $f_1(1285)$; in this way, a peak at $\sim$1290 MeV can be identified as one of the two states. The L3 collaboration studied $\gamma\gamma^*$ and $\gamma\gamma \to K_s^0 K^\pm \pi^\mp$. At low q^2, a peak at 1440 MeV is seen, it requires high q^2 to produce a peak at 1285 MeV. A pseudoscalar state is produced also at vanishing q^2 while $J^{PC} = 1^{++}$ is forbidden for $q^2 \to 0$. Hence the structure at 1285 MeV is due to $f_1(1285)$ and not due to $\eta(1295)$. There is no evidence for $\eta(1295)$ from $\gamma\gamma$ fusion. The stronger peak contains contributions from $\eta(1440)$ and $f_1(1420)$ [9]. The coupling of the $\eta(1440)$ meson to photons is stronger than that of the $\eta(1295)$: the assumption that the $\eta(1295)$ is a $(u\bar{u} + d\bar{d})$ radial excitation must be wrong!

4 The $\eta(1295)$ and $\eta(1440)$ in $p\bar{p}$ annihilation

The Crystal Barrel collaboration searched for the $\eta(1295)$ and $\eta(1440)$ in the reaction $p\bar{p} \to \pi^+\pi^-\eta(xxx)$, $\eta(xxx) \to \eta\pi^+\pi^-$. The search was done by assuming the presence of a pseudoscalar state of given mass and width, mass and width are varied and the likelihood of the fit is plotted. Fig. 1 shows such a plot [13]. A clear pseudoscalar resonance signal is seen at 1405 MeV. Two decay modes are observed, $a_0(980)\pi$ and $\eta\sigma$ with a ratio 0.6 ± 0.1. We use the notation σ for the full $\pi\pi$ S–wave.

A scan for an additional 0^+0^{-+} resonance provides no evidence for the $\eta(1295)$ but for a second resonance at 1480 MeV, see Fig. 1, with $M = 1490 \pm 15, \Gamma = 74 \pm 10$. This is the η_H. It decays to $a_0(980)\pi$ and $\eta\sigma$ with a ratio 0.16 ± 0.10. This data provides the first evidence for $\eta_H \to \eta\pi\pi$ decays.

The phenomena observed in the pseudoscalar sector are confusing: The $\eta(1295)$, the assumed radial excitation of the η, is only seen in $\pi^-p \to n(\eta\pi\pi)$, not in $p\bar{p}$ annihilation, nor in radiative J/ψ decay, nor in $\gamma\gamma$ fusion. In all these reactions it should have been observed. There is no reason for it to have not been produced if it is a $\bar{q}q$ state. On the other hand, we do not expect glueballs, hybrids or multiquark states so low in mass. In the 70's, the properties of the $a_1(1260)$ were obscured by the so–called Deck effect (ρ–π re-scattering in

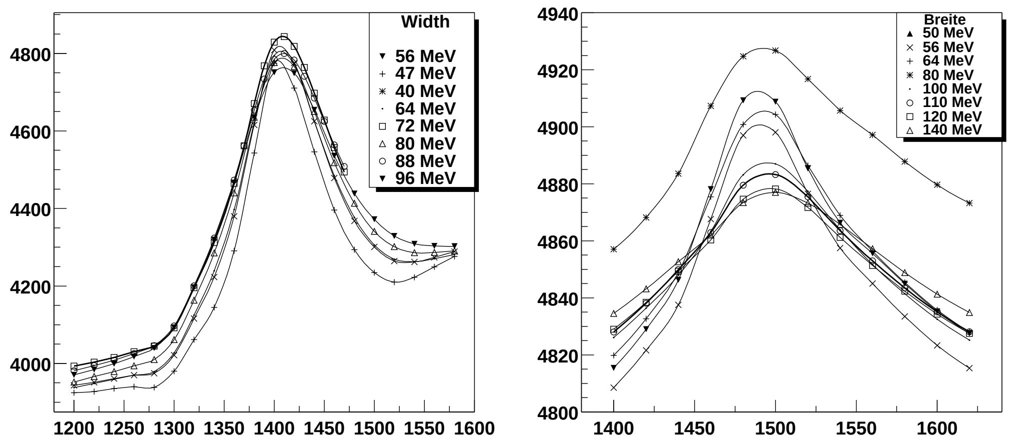

Figure 1. Scan for a 0^+0^{-+} resonance with different widths [13]. The likelihood optimizes for $M = 1407 \pm 5, \Gamma = 57 \pm 9\,\text{MeV}$. The resonance is identified with the η_L. A search for a second pseudoscalar resonance (right panel) gives evidence for the η_H with $M = 1490 \pm 15, \Gamma = 74 \pm 10\,\text{MeV}$.

the final state). Possibly, $a_0(980)\pi$ re-scattering fakes a resonant–like behavior but the $\eta(1295)$ is too narrow to make this possibility realistic. Of course there is the possibility that the $\eta(1295)$ is mimicked by feed–through from the $f_1(1285)$. In any case, I exclude the $\eta(1295)$ from the further discussion.

The next puzzling state is the $\eta(1440)$. It is not produced as $\bar{s}s$ state but decays with a large fraction into $\mathrm{K\bar{K}}\pi$ and it is split into two components. I suggest that the origin of these anomalies is due to a node in the wave function of the $\eta(1440)$! This node has an impact on the decay matrix elements calculated by Barnes *et al.* [14] within the $^3P_0$ model.

5 E/ι decays in the $^3P_0$ model

The matrix elements for decays of the $\eta(1440)$ as a radial excitation ($=\eta_R$) depend on spins, parities and decay momenta of the final state mesons. For η_R decays to $\mathrm{K^*K}$, the matrix element is given by

$$f_P = \frac{2^{9/2} \cdot 5}{3^{9/2}} \cdot x \left(1 - \frac{2}{15} x^2\right).$$

In this expression, x is the decay momentum in units of 400 MeV/c; the scale is determined from comparisons of measured partial widths to model predictions. The matrix element vanishes for $x = 0$ and $x^2 = 15/2$, or $p = 1\,\text{GeV/c}$. These zeros have little effect on the shape of the resonance.

The matrix element for η_R decays to $a_0(980)\pi$ or $\sigma\eta$ has the form

$$f_S = \frac{2^4}{3^4} \cdot \left(1 - \frac{7}{9}x^2 + \frac{2}{27}x^2\right)$$

and vanishes for $p = 0.45\,\mathrm{GeV/c}$. The decay to $a_0(980)\pi$ vanishes at the mass 1440 MeV. This has a decisive impact on the shape, as seen in Figure 2. Shown are the transition matrix elements as given by Barnes et al. [14] and the product of the squared matrix elements and a Breit–Wigner distribution with mass 1420 MeV and width 60 MeV.

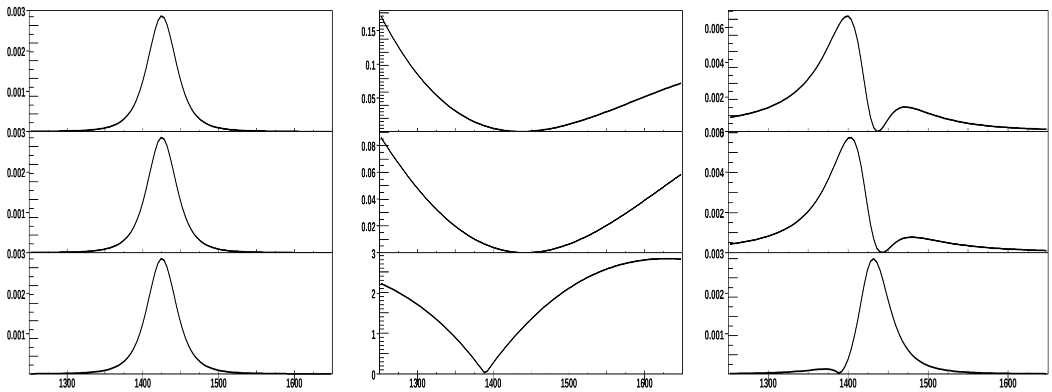

Figure 2. Amplitudes for $\eta(1440)$ decays to $a_0\pi$ (first row), $\sigma\eta$ (second row), and $\mathrm{K}^*\bar{\mathrm{K}}$ (third row); the Breit-Wigner functions are shown on the left, then the squared decay amplitudes [14] and, on the right, the resulting squared transition matrix element.

The $\eta(1440) \to a_0(980)\pi$ and $\to \mathrm{K}^*\mathrm{K}$ mass distributions have different peak positions; at approximately the η_L and η_H masses. Hence there is no need to introduce the η_L and η_H as two independent states. One $\eta(1420)$ and the assumption that it is a radial excitation describe the data.

This conjecture can be further tested by following the phase motion of the $a_0(980)\pi$ or $\sigma\eta$ isobar [13]. The phase changes by π and not by 2π, see Fig. 3.

6 Conclusions

Summarizing, the results for the radial excitations of pseudoscalar mesons are as follows:

- The $\eta(1295)$ is not a $q\bar{q}$ meson.
- The $\eta(1440)$ wave function has a node leading to two appearantly different states η_L and η_H.

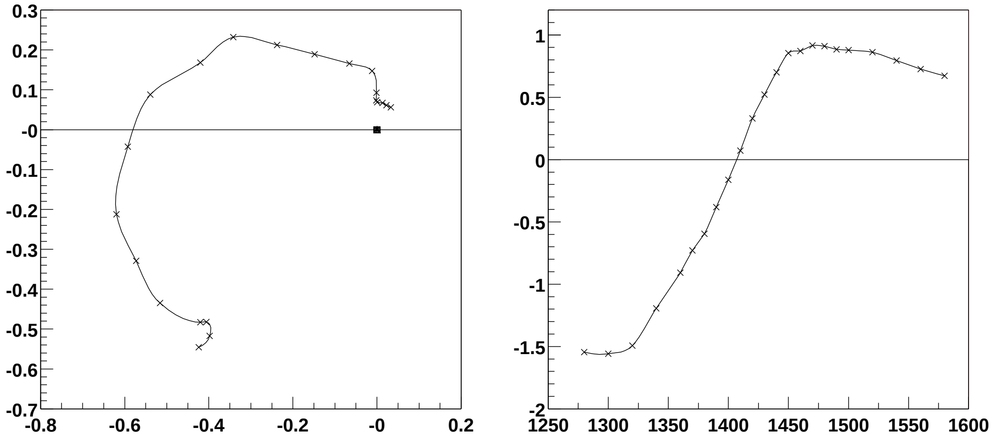

Figure 3. Complex amplitude and phase motion of the $a_0(980)\pi$ isobars in $\mathrm{p\bar{p}}$ annihilation into $4\pi\eta$. In the mass range from 1300 to 1500 MeV the phase varies by π indicating that there is only one resonance in the mass interval. The $\sigma\eta$ (not shown) exhibits the same behavior [13].

- There is only one η state, the $\eta(1420)$, in the mass range from 1200 to 1500 MeV and not 3 !
- The $\eta(1440)$ is the radial excitation of the η. The radial excitation of the η' is expected at about 1800 MeV; it might be the $\eta(1760)$.

The following states are most likely the pseudoscalar ground states and radial excitations:

1^1S_0	π	η'	η	K
2^1S_0	$\pi(1300)$	$\eta(1760)$	$\eta(1440)$	K(1460)

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