Radial excitations of pseudoscalar mesons

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The $\eta(1440)$ seems to be split into two components, an $\eta(1410)$ and an $\eta(1470)$. The splitting might signal a node in the $\eta(1440)$ wave function suggesting that the $\eta(1440)$ is a radial excitation. The partial width of the $\eta(1440)$ for the $\rho\gamma$ decay leaves a little room for an exotic interpretation of the $\eta(1440)$. The production rate of the $\eta(1440)$ in $\bar{\mathrm{p}}\mathrm{p}$ annihilation is similar to that of the $\pi(1300)$ which was observed in its $\rho\pi$ decay. No evidence was observed for the $\eta(1295)$. If the latter exists its production must be much weaker than that of the $\pi(1300)$ by about a factor 100. If the latter is assigned to the 2^1S_0 nonet, the $\eta(1295)$ cannot belong to this nonet. Then a new pseudoscalar nonet emerges consisting of $\pi(1300)$, $\eta(1440)$, $\eta(1760)$ and K(1460).

1. INTRODUCTION

The Particle Data Group [1] suggests that the radially excited pseudoscalar nonet should consist of the $\pi(1300)$, $\eta(1295)$, $\eta(1440)$ and K(1460). Our knowledge on pion and kaon radial excitations is limited. The mass of the $\pi(1300)$ scatters over a wide range and its width is rather uncertain[2,3]. For the K(1460) the situation is even worse; only two experiments reported evidence for pseudoscalar intensity in the $\mathrm{K}\pi\pi$ system [4,5].

There are some problems with the radially excited pseudoscalar nonet. Firstly, the small mass difference between the $\eta(1295)$ and the $\pi(1300)$ suggests a nearly ideal mixing angle for the pseudoscalar nonet and hence a $\mathrm{s}\bar{\mathrm{s}}$ structure of the higher mass η state. This assignment is in conflict with the strong appearance of the $\eta(1440)$ in $\pi^-\mathrm{p}\to\overline{\mathrm{K}}\mathrm{K}\pi\mathrm{n}$ [6–9] and its absence in $\mathrm{K}^-\mathrm{p}\to\overline{\mathrm{K}}\mathrm{K}\pi\Lambda$ [10]. And the mass of the $\eta(1440)$ is too low as the $\mathrm{s}\bar{\mathrm{s}}$ partner of the $\eta(1295)$. The other problem is that $\eta(1440)$ seems to be split into two components, an $\eta(1410)$ and an $\eta(1470)$.

These difficulties and the strong yield of the $\eta(1440)$ in radiative J/ψ decays have substantiated the claim that the $\eta(1440)$ should be a pseudoscalar glueball, an interpretation which has been taken up recently by Close [11] and by Minkowski and Ochs [12]. Quenched lattice calculations predict pseudoscalar glueball masses significantly above 2 GeV [13]; hence Farrar suggested to interpret the $\eta(1440)$ as bound state of gluinos [14].

These interpretations depend heavily on the interpretation of the $\eta(1295)$ as a $\bar{\mathrm{q}}\mathrm{q}$ state. The most recent particle data listings quote 3 experiments [15–17] in which the $\eta(1295)$ is seen in pion-induced reactions. But while the $\eta(1440)$ is clearly observed in radiative J/ψ decays [18] and in $\bar{\mathrm{p}}\mathrm{p}$ annihilation at rest[19], there is no evidence for the $\eta(1295)$ in the latter two reactions.

2. THE $\eta(1440)$ AS THE FIRST RADIAL INTERPRETATION OF THE η

Here, the $\eta(1440)$ is interpreted as the first radial interpretation of the η, because of the following 3 reasons.

2.1. $\eta(1295)$ is likely not a 2^1S_0 state

Recently the Crystal Barrel Collaboration found the mass of the $\pi(1300)$ $M(\pi(1300)) = (1375\pm40)$ [2] and production rates. In table 1 we compare branching ratios for production of $\sigma\pi$ and $\sigma\eta$ with those for $\sigma\pi(1300)$ and $\sigma\eta(1295)$ or $\sigma\eta(1440)$. The $\eta(1440)$ is observed

Table 1
Branching ratios in $\bar{p}p$ annihilation

Reaction	Rate $[10^{-3}]$	Reaction	Rate $[10^{-3}]$
$\bar{p}p\to\sigma\pi$	~ 6	$\bar{p}p\to\sigma\eta$	~ 5
$\bar{p}p\to\sigma\pi(1375)$	~ 6	$\bar{p}p\to\sigma\eta(1295)$	< 0.04
$\bar{p}p\to\sigma\pi(1375)$	~ 6	$\bar{p}p\to\sigma\eta(1440)$	~ 5

with a rate for $\bar{p}p\to\pi\pi\eta(1440)$ which is only three times smaller than the rate for $\pi\pi\eta$. The $\eta(1295)$ is not observed at all. There is no evidence for the $\eta(1295)$ in the J/ψ decays either. Based on the rate comparisons we suggest that the $\eta(1295)$ is not a $\bar{q}q$ state. This observation makes the $\eta(1440)$ a better candidate for the η radial excitation than the $\eta(1295)$.

2.2. $\eta(1440)$ is not an exotic state

The low-mass part of the $\eta(1440)$ is likely observed to decay into $\rho\gamma$ by MarkIII[20] and DM2[18] with a partial width of (1.6 ± 0.6) MeV[1]. The η' has a $\rho\gamma$ partial width of (0.061 ± 0.005) MeV[1]. Radiative transition rates should scale approximately with the decay momentum ratio to the third power. Then we can calculate the ratio of the partial widths and the decay momentum to the third power:

$$\frac{\Gamma_{\eta'\to\gamma\rho}/p^3_{\eta'\to\gamma\rho}}{\Gamma_{\eta(1440)\to\gamma\rho}/p^3_{\eta(1440)\to\gamma\rho}} = (1.07 \pm 0.41) \approx 1 \tag{1}$$

This gives a little room for an exotic interpretation of the $\eta(1440)$.

2.3. Splitting of the $\eta(1440)$: evidence for 2^1S_0 state

The splitting of the $\eta(1440)$ into a $\eta(1410)$ and a $\eta(1470)$ provides direct evidence that the $\eta(1440)$ should be a radial excitation: in the $^3P_0$ model[21] the $\eta(1440)$ decays into $a_0(980)\pi$ with a transition operator given by

$$\mathcal{M}_{a_0(980)\pi} = \text{const.} \cdot (1 - \frac{7}{9}x^2 + \frac{2}{27}x^4) \cdot e^{-x^2/12} \tag{2}$$

where x is proportional to the decay momentum. A momentum scaling factor is deduced from a comparison of calculated mesonic partial decay widths with experiment. The matrix element $\mathcal{M}_{a_0(980)\pi}$ vanishes for $x = 1.22$. Adopting this value for x, the $\eta(1440)$

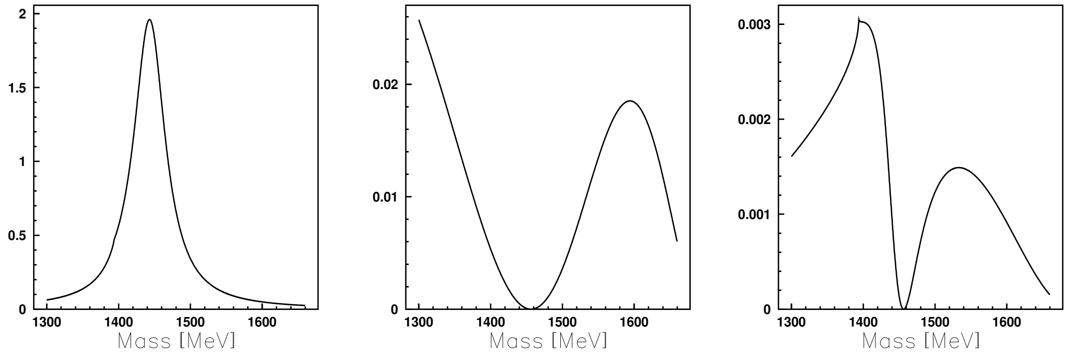

Figure 1. Splitting of the $\eta(1440)$ in the decay into $a_0(980)\pi$. (a:left): a Breit Wigner with a mass of 1445 MeV and a with of 105 MeV, (b:centre): square of the matrix element $\mathcal{M}_{a_0(980)\pi}$, (c:right): multiplication of a and b.

into $a_0(980)\pi$ decay amplitude vanishes at 1450 MeV (Fig. 1b) and the $a_0(980)\pi$ decay is allowed only for masses below and above this mass (Fig. 1c).

In the ${}^3P_0$ model a transition operator for the $\eta(1440)$ decay into K*K is

$$\mathcal{M}_{\mathrm{K^*K}} = \mathrm{const.} \cdot x(1 - \frac{2}{15}x^2) \cdot e^{-x^2/12} \tag{3}$$

The K*K decay mode does not have a zero in the mass range we consider, and hence the nominal $\eta(1440)$ mass should be observed in this isobar amplitude. The hypothesis that the $\eta(1440)$ is a radial excitation and that the ${}^3P_0$ model governs its decay leads therefore to a splitting of the $\eta(1440)$ region into a low-mass and a high-mass state in the $a_0(980)\pi$ isobar and no splitting in the K*K decay mode. It is a very crude model: it assumes harmonic oscillator wave functions, neglects $\sigma\eta$ decay of $\eta(1440)$. Rescattering effects can dilute this possibly too naive picture. But it teaches us that the splitting of a state into two states may evidence that the state is a radial excitation.

3. NEW NONET OF THE RADIAL EXCITATIONS OF PSEUDOSCALAR MESONS

Obviously, the $\eta(1440)$ is a much better isoscalar companion of the $\pi(1300)$ than the $\eta(1295)$. Its production strength falls behind expectations by at least one order of magnitude while the $\eta(1440)$ is observed at a rate expected for the isoscalar companion of the $\pi(1300)$. Based on the rate comparisons we suggest to interpret the $\eta(1295)$ not as $\bar{\mathrm{q}}\mathrm{q}$ state but as crypto-exotic, e.g. as four-quark state, or to scrutinize its existence. With the $\eta(1295)$ not used as member of the pseudoscalar meson octet of radial excitations, a natural choice now are the states:

$$\pi(1300) \qquad K(1460) \qquad \eta(1440) \qquad \eta(1760) \tag{4}$$

With the help of the GMO formula (and the same definition of the mixing angle for the radial excitation as for the ground states) we find

$$\Theta_{2^1S_0} = -(16 \pm 16)^\circ \tag{5}$$

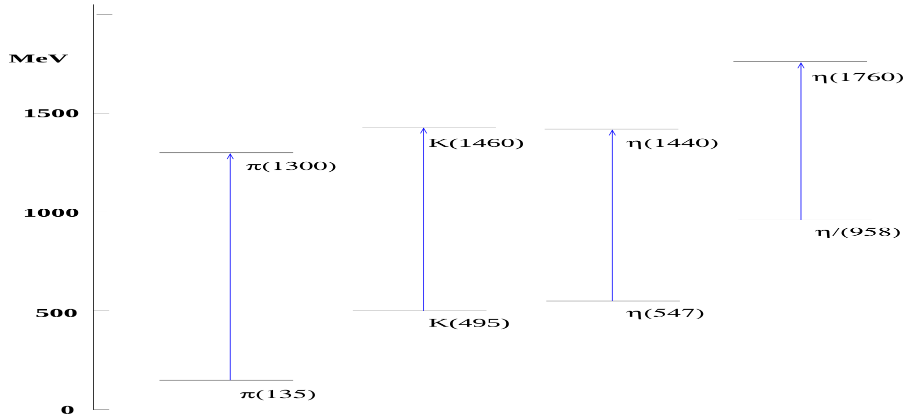

Figure 2. Radial excitations of the pseudoscalar mesons

where the error covers a spread of the $\pi(1300)$ mass of (1300 ± 100) MeV and of the K(1460) mass of (1430 ± 30) MeV. Note that large masses of the $\pi(1300)$ and small ones for the K(1460) lead to no solution for the mixing angle. The result suggests that the pseudoscalar mixing angle for the first radial excitation is small and not so different from the ground state mixing angle.

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