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Experimental status of the E/ι puzzle

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Despite the prolonged experimental effort devoted to the spectroscopy of the E/ι mesons, and the intense theoretical debate around this subject, many puzzling issues still prevent from a full understanding of the true scenario. The advent of new and more precise experimental measurements motivates a review on this topic.

1. INTRODUCTION

One of the most stimulating evidence of the existence of exotic states, predicted by QCD, has been the discovery, in light meson spectroscopy, of a pseudoscalar state, ι or $\eta(1420)$, suspected to be a glueball. The first evidence of such state dates back to 1967, with antiprotons at rest in a liquid hydrogen bubble chamber [1]. Since then, many groups have claimed evidence of it from many different production processes, sometime questioning its intrinsic pseudoscalar nature. Indeed, it is now certain that multiple states with pseudoscalar (ι) and axial vector (E) quantum numbers populate the mass spectra of the systems ($K\bar{K}\pi$, $\eta\pi\pi$, 4π, etc.) into which the E/ι mesons decay. Despite their narrow widths such states are so close in mass to cause some confusion and to lead to persistent inconsistencies among different experimental measurements. This is in part the reason why this subject still lacks of a firm theoretical interpretation. Indeed, the main reason of such delay is the fact that light meson spectroscopy probes the non-perturbative domain of QCD, where systematic calculations are not yet available and modelling seems the only reasonable theoretical approach. In this report, we will focus on the most recent experimental results and make an effort to provide a consistent picture of the whole subject. A recent review has been presented last year by Nichitiu [2].

2. MOST RECENT EXPERIMENTAL MEASUREMENTS

The past two years have provided a series of high quality, large statistics experimental results on the E/ι spectroscopy.

The $\eta\pi^0\pi^0$ decay final state has been explored at 100 GeV/c, ($-t > 0.15$ (GeV/c)^2), in the charge exchange reaction $\pi^- p \to \eta\pi^0\pi^0 n$ by the GAMS collaboration. A spin-parity analysis of the $\eta\pi^0\pi^0$ system, performed within the framework of the isobar model, has been presented at this Conference [3]. The results have shown that both 0^{-+} and 1^{++} partial amplitudes contribute in the E/ι region (1.4 to 1.5 GeV). The pseudoscalar $\iota/\eta(1420)$ ($M = 1424 \pm 6, \Gamma = 85 \pm 18$ MeV) has a dominant direct 3-body decay $\eta(\pi\pi)_S$, where $(\pi\pi)_S$ is the S-wave dipion amplitude, and a much weaker $a_0\pi^0$ decay. The axial vector $f_1(1420)$ ($M = 1435 \pm 9, \Gamma = 90 \pm 25$ MeV), roughly seven times less intense than the pseudoscalar, is seen only decaying to $a_0\pi^0$. The analysis provides in addition evidence of the pseudoscalar $\eta(1295)$ and the axial vector $f_1(1285)$ in the subsystem $a_0\pi^0$.

The same decay system, namely $\eta\pi^0\pi^0$, has been explored last year by the CRYSTAL BARREL collaboration in studying the annihilation at rest of antiprotons in a liquid hydrogen target into the final state $\eta + 4\pi$ [4]. The spin-parity analysis of a large statistics data sample confirms the main characteristics of the $\eta(1420)$ as found by GAMS, namely the spin, the mass and width, and the large $\eta(\pi\pi)_S$ decay branching, although with an intensity comparable to the $a_0\pi^0$ mode

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and not 4 times larger, as in the GAMS result. Furthermore, the contribution from $\eta(1295)$ (significative in GAMS) is found to be very marginal, whereas the axial vector component is only at the percent level.

The CRYSTAL BARREL data set provides the first evidence of $\eta(1420) \rightarrow \eta\pi\pi$ in annihilation of antiprotons at rest. Earlier evidence was reported 25 years ago from the analysis of a sample of in-flight annihilations at low $\bar{p}$ momentum (720 MeV/c) [5]. These results already indicated indirectly a sizeable three-body contribution to the $\eta(1420)$ total decay rate.

The parameterization of such decay in terms of a S-wave $(\pi\pi)$ bound to a η was first formally introduced in the partial wave analysis (PWA) of 8 GeV/c $\pi^- p \rightarrow \eta\pi^+\pi^- n$ data from KEK [6]. The results of the analysis confirmed the presence of a pseudoscalar signal and indicated a strong negative interference, near 1420 MeV (relative phase $= 150^o$), between the 0^{-+} $a_0\pi$ and $\eta(\pi\pi)_S$ partial waves. This destructive effect might explain why the $\eta(1420)$ signal in the $\eta\pi\pi$ system is not as clearly observed as in the $K\bar{K}\pi$ mass spectrum.

The most recent results on the study of the $K\bar{K}\pi$ final state come from the experiments: E690 at Fermilab [7], BES at Bepc [8] and OBELIX at Lear [9]. Three different production mechanisms were employed: central collisions, J/ψ radiative decays and $\bar{p}p$ annihilations at rest, respectively.

The $K^0_s K^\pm \pi^\mp$ system produced in pp collisions at 800 GeV/c, away from beam and target particles, was analyzed in terms of a partial wave decomposition describing the $a_0\pi$ and $K^*\bar{K}$ dimeson amplitudes. Alike all previous results from high energy hadron beam experiments, E690 isobar analysis confirms the presence of axials and the absence of pseudoscalars in the centrally produced $K\bar{K}\pi$ system [7]. Both $f_1(1285)$ and $f_1(1420)$ are observed through their decay into $a_0\pi$ and $K^*\bar{K}$ intermediate state, respectively.

From a sample of 8 million J/ψ decays the BES collaboration has performed a recent analysis of a few hundred events in which the $K^0_s K^\pm \pi^\mp$ and $K^+K^-\pi^0$ systems recoil against a radiative photon [8]. From the fit of 3-body decay moments, extracted from the $K\bar{K}\pi$ angular distributions, they receive evidence of one pseudoscalar ($M = 1467 \pm 3, \Gamma = 89 \pm 6$ MeV) and two axial vector states ($M_1 = 1435 \pm 3, \Gamma_1 = 59 \pm 5$ MeV and $M_2 = 1497 \pm 2, \Gamma_2 = 44 \pm 7$ MeV). The result of their moment analysis is not in complete agreement with the isobar analyses performed earlier by the MARK III [10] and DM2 [11,12] groups. (After all a disagreement on the spin-parity sequence of states and on their decay still exists between the SLAC and DCI analyses). It is at least certain that three states overlap and interfere in the $K\bar{K}\pi$ mass spectrum. Two of them most likely correspond to the $\eta(1420)$, observed in the $\eta\pi\pi$ system by GAMS and CRYSTAL BARREL, and the $f_1(1420)$ seen again by GAMS and in all central production experiments. The third state, pseudoscalar (MARK III and DM2) or axial vector (BES), is only seen in the $K\bar{K}\pi$ system because it decays via a $K^*\bar{K}$ intermediate state (not confirmed by BES).

There has been a recent re-analysis of $J/\psi \rightarrow \gamma(4\pi)$ events [13] in which a strong pseudoscalar signal decaying into $\rho\rho$ is claimed. The mass coincide with the $\eta(1420)$, but its width ($\sim$ 160 MeV) is much broader. Before concluding that this state is another manifestation of the $\eta(1420)$ further experimental input is needed.

A confirmation of the existence of an additional state, seen together with $\eta(1420)$ and $f_1(1420)$, has come last year from a study of $\bar{p}p \rightarrow K^0K^\pm\pi^\mp\pi^+\pi^-$ annihilations at rest in a liquid hydrogen target performed by the OBELIX collaboration at Lear [9].

From a sample of 18 million annihilations, OBELIX has extracted a sizeable sample ($\sim$ 4000 events) of $K^0K^\pm\pi^\mp\pi^+\pi^-$ (with a missing K^0). Despite the presence of a residual 20% background and the limited acceptance on the charged $K^* \rightarrow K^0\pi^\pm$, the neutral $K\bar{K}\pi$ invariant mass spectrum shows a prominent, structured signal at 1.4 GeV. The spin-parity analysis, performed in the hypothesis of S and P initial wave contributions, reveals the presence of two pseudoscalar states (as expected due to the dominance of S-wave annihilation), at $M = 1416 \pm 2, \Gamma = 50 \pm 4$ MeV and $M = 1460 \pm 10, \Gamma = 105 \pm 15$ MeV, respectively. Unlike the $\eta\pi\pi$ system, the $K\bar{K}\pi$ mass spectrum appears saturated by two such resonances. Their decay pattern is however somewhat different. For the lighter of the two a direct three body decay is confirmed to be the dominant mode, whereas the heavier state decays almost entirely through $K^*\bar{K}$. The discovery of a large $(K\pi)_S\bar{K}$ decay rate weakens the significance of the $a_0\pi$ decay mode, considered dominant in all previous analyses of the $K\bar{K}\pi$ system, providing new indications on the decay pattern of this state. The second pseudoscalar, whose existence is also confirmed by the phase motion of the $K^*\bar{K}$ partial amplitude, as shown by the OBELIX PWA, is seen for the first time in antiproton annihilations at rest. Its parameters, namely mass and width, are in agreement with those published by MARK III; its dominant $K^*\bar{K}$ decay mode explains why it is not observed in the $\eta\pi\pi$ system. The data below the $K\bar{K}\pi$ mass of 1400 MeV report, contrary to expectation, no evidence of another pseudoscalar: the $\eta(1295)$.

The OBELIX collaboration has very recently analyzed an additional data sample of about 24 million antiproton annihilations at rest in a gaseous hydrogen target into the same final state, namely $K^0K^\pm\pi^\mp\pi^+\pi^-$ [14]. The aim was to search, within the E/ι mass region, for possible axial vector resonances produced from initial protonium P-wave. Indeed, the preliminary results of the global fit and of the PWA seem to confirm the two pseudoscalars and provide some evidence of a third resonance, with $J^{PC} = 1^{++}$, located in between the $\eta(1420)$ and the $\eta(1460)$. Its intensity is at the level of a few percent, comparable to the intensity of the $f_1(1285) \to a_0\pi$ observed in the same mass spectrum, and the dominant decay is through $K^*\bar{K}$. Mass and width are in good agreement with the results from central production, J/ψ radiative decays and some very old measurements with $\bar{p}$ in flight (700 MeV/c) [15,16]. However, all those experiments report a width slightly narrower than the one found by GAMS in the $f_1(1420) \to \eta\pi\pi$ decay mode. Incidentally, there seem to be a disagreement also on the value of the total width of the lighter of the two pseudoscalars measured in the $\eta\pi\pi$ and $K\bar{K}\pi$ decay modes, with the former systematically wider than the latter one.

In two-photon reactions, for which more data are badly needed, the radiative width of the axial vector $f_1(1420)$ has been (poorly) measured in single-tag $K\bar{K}\pi$ events. On the contrary, there is no sign of pseudoscalar production in no-tag events [17–20].

Two consequences derive from the preceeding summary of the most recent experimental activities. First: all final states which allow the investigation of the $K\bar{K}\pi$ system seem the most appropriate for resolving the complexity of the E/ι spectrum, as they provide evidence of three adjacent states, with a favourable signal to noise ratio. The $\eta\pi\pi$ system provides complementary information on only two of such states ($\eta(1420)$ and $f_1(1420)$), due presumably to the absence of the $K^*(892)$, which appears to characterize the main decay properties of the third state. Second: we have observed how the production mechanism plays a crucial role in leading to excitation of specific quantum numbers (central production and single-tag two-photon collisions) or simultaneously of all of them (peripheral and annihilation reactions).

In order to establish the intrinsic nature of the resonances observed in the E/ι mass region it is then necessary to fully understand their production and decay properties.

3. E/ι PRODUCTION

In this section we outline the main characteristics of the different production mechanisms which have lead to the observation of the states discussed above. We shall begin with the ones which appear more restrictive on the quantum numbers of the produced objects.

In high energy hadronic *central collisions* the resonance production mechanism is marginally known. Assuming a double exchange process, one may assume that at small $t = t_1 + t_2$ resonances are produced in a doubly diffractive process in which the exchanged particle is a Pomeron. With this hypothesis the differential cross section for the Double Pomeron Exchange (DPE) features an exponential behaviour (at small t) and increasing with center-of-mass energy. Conventional quarkonium states with $PC = ++$ are overwhelmingly produced at large t, where DPE is suppressed (and cross sections decrease with increasing s). Enhanced production at small t might therefore be a signature of exotism. Both the $f_0(970)$ (but not the $a_0(980)$) and the $\theta(1720)$ are abundant in the DPE limit. The $f_1(1420)$ production is instead suppressed at small t and its cross section is independent of s [21].

Two–photon couplings of resonances produced in e^+e^- storage rings is a better known process. The initial state is represented by the QED coupling of photons to quarks (and antiquarks). The cross section for resonance production in $\gamma\gamma$ fusion is related to the product of the resonance spin, its total width and its partial width for the decay into two real photons. The two-photon partial width is a function of the $\gamma\gamma - q\bar{q}$ coupling constant which, in turn, is proportional to the square of the quark charge. Therefore, coupling of glueball to photons is suppressed (to $O(\alpha_s^2)$) in $\gamma\gamma$ fusion. Two other important consequences are: a state coupling to two real photons must have $C = +1$, and two-photon coupling of a spin-one resonance vanishes. These selection rules do not apply when one (or both) photons are off-mass shell and acquire both polarization states. In one-tag ($\gamma\gamma^*$) processes Yang's theorem [22] is overcome and, in this circumstance, production of $f_1(1420)$ is observed. On the contrary, both $\eta(1420)$ and $\eta(1460)$ have a weak $\gamma\gamma$ coupling. The upper limit on the $\eta(1420)$ to two-photon partial width is still the one established by CELLO [19]:

$$\Gamma_{\gamma\gamma} * B(\eta_{1420} \to K\bar{K}\pi) < 1.2\ KeV\ (95\%\ c.l.) \quad (1)$$

The $\gamma\gamma$ partial width would be zero in a world without quarks, since gluons are insensitive to the electro-magnetic interaction. It would seem therefore that the quark content of these two pseudoscalars is anomalously small for them to be conventional $q\bar{q}$ mesons.

This argument is supported by the observation of a copious production of $\eta(1420)$ and $\eta(1460)$ in *J/ψ radiative decays*. Such processes are considered to be a potential source of gluonic mesons. The two-gluon plus the radiative photon system, is expected to be strongly coupled ($O(\alpha\alpha_s^2)$) to two-gluon bound states of similar quantum numbers, and less coupled ($O(\alpha\alpha_s^4)$) to ordinary mesons with $C = +1$ and $I = 0$. However such prediction is weakened by the non-perturbative aspect of the two-gluon coupling which only at the heavy quark ($c\bar{c}$) vertices can be computed at all orders in perturbation theory. Once theorists converge towards a universal definition of the "*gluonic width*" of a light resonance then experimental decay widths of radiative decays of heavy quarkonia provide a mean to determine its gluonic component [23].

Experimentalists, on their side, (and the BES group in primis) are encouraged to provide, whenever accessible, clear signatures in *hadronic J/ψ decays*. The argument is well known and relies on the fact that glue is flavorless and therefore insensitive to the quark flavour of the hadron it couples to (ω, ϕ). Flavour blindness should therefore be observed in the decay of a pure glueball. This is true to some extent, as reactions governed by gluon exchange can manifest dependence on the mass of the quarks to which it couples. Moreover, the mixing with valence $q\bar{q}$ pairs might partially invalidate the above argument. Unfortunately the scarce experimental results on hadronic J/ψ decays available up to now [24] don't help in clarifying the nature of the states observed in the E/ι mass region.

Remarkable has been the experimental effort devoted in the recent years from the Lear community to the E/ι spectroscopy with antiprotons. Both CRYSTAL BARREL and OBELIX, but before ASTERIX [25], and long ago several bubble chamber experiments, are providing stimulating results from the study of the annihilation at rest of antiprotons in hydrogen targets.

The *$\bar{p}p$ annihilation* at low energy is a complicated process, involving the annihilation of $q\bar{q}$ pairs and/or their rearrangement. Due to the finite size of the interaction volume, typical of low Q^2 processes, additional degrees of freedom, like meson or baryon exchange, cannot be neglected. The annihilation dynamics is, in addition, sensible to final state interactions among the emerging particles which affect their production rates. Predictions are therefore limited in most cases by the hypotheses introduced to build specific theoretical models. A valuable input to the theory comes from accurate measurements of two-body branching ratios at rest, for which the underlying dynamics should appear more elementary. Their determination should provide indication on the relative strength between the quarks annihilation and rearrangement mechanisms [26–28], and therefore on the nature of the exchanged particle. Indeed, the measured ratios of two-body branching ratios at rest (if for the $\eta\eta$ to $\pi^0\pi^0$ ratio one uses an old value [29] of the $\pi^0\pi^0$ branching ratio in liquid hydrogen, instead of a more recent determination [30]) all yield a consistent value of the pseudoscalar mixing angle of $\sim 20^o$ - in agreement with other determinations [31] - if dominance of the annihilation mechanism over the rearrangement is assumed. Processes mediated by gluon exchange (like presumably $\bar{p}p$ at rest) might lead to enhanced coupling to gluon rich bound states. In annihilations at rest the production of the pseudoscalars $\eta(1420)$, $\eta(1460)$ and the axial vector $f_1(1420)$ is observed in the $K\bar{K}\pi$ system. Since there is no access to the $K^*\bar{K}$ intermediate state, the $\eta\pi\pi$ system does only account for the lighter of the two pseudoscalars. Its total width of 86 ± 10 MeV, as measured by CRYSTAL BARREL [4], is however larger than the one reported by OBELIX (50 ± 4 MeV) in the $K\bar{K}\pi$ decay mode [9]. It is possible that the opening of the $K^*\bar{K}$ threshold is responsible for the narrowing of the $\eta(1420)$ apparent width in the $K\bar{K}\pi$ decay system.

The *peripheral production* of resonances in hadronic processes is the least restrictive in selecting specific final states. In practice everything can be produced, both conventional and exotic mesons. The t dependence of the production cross section features *unnatural* ($P \neq (-1)^J$) OPE mechanism at small $|t|$ (J^{PC}=$even^{++}$,odd^{--} are produced), and *natural* (K^*, ρ, *reggeon*) exchanges at large $|t|$ values, where rescattering mechanisms may affect the production of wide resonances. As an example, the $K\bar{K}\pi$ system produced in $\pi^-p, K^-p, \bar{p}p$ interactions at 8 GeV/c has shown simultaneously $\eta(1420)$, $\eta(1460)$, $f_1(1420)$ and the $J^{PC} = 1^{+-}$ $h_1(1380)$ resonances [32]. In the $C = +1$ $K_s^0K_s^0\pi^0$ final state the two pseudoscalars appear enhanced at large $|t|$ (but $\eta(1295)$ is suppressed), whereas the production of the axial vector $f_1(1420)$ seems dominant at small $|t|$ values (but $f_1(1285)$ is suppressed) [33].

4. E/ι DECAY

In the previous sections we have seen that flavour democracy in the gluon couplings to $q\bar{q}$ pairs implies, with some caution [34], equal decay branching ratios to multi-particle final states, apart from phase space factors of the type q^{2l+1}. This argument applies to a pure glueball; however mixing with $q\bar{q}$ mesons of identical J^{PC} and comparable mass might cause modification in the decay properties. In particular mixing is considered responsible for violations of the OZI rule in a specific nonet, quantified in large deviations of the mixing angle from the ideal value. Therefore glueballs, hybrids and multiquark states must all be studied against the background of nearby conventional mesons. The naive expectation on the uniqueness of the decay properties of pure glueballs is the basic assumption of (quenched) lattice gauge theory. If glueballs are not very broad objects one expects stability in the mass prediction independently of their quark admixture [35].

The observation of a large deviation from ideal mixing in the ground state pseudoscalar nonet might provide indirect evidence of a large gluonic component mixed with the ordinary nonet members. Based on such assumption several mixing models with $\eta - \eta' - \iota$ (where ι represents an almost pure 0^{-+} glueball) have been proposed in order to calculate the radiative decay widths of pseudoscalars [37–41]. In case the pseudoscalar radiative width is experimentally measured its value is used as input to determine the probability of octet and singlet component from the parameters of the mass mixing matrix. Unfortunately only upper limits exist on the two-gamma partial decay widths of $\eta(1420)$ and $\eta(1460)$. One can predict $\Gamma_{\gamma\gamma}$ of the $\eta(1420)$ using the CELLO limit given above [19] and assuming knowledge of the absolute $\eta(1420) \to K\bar{K}\pi$ branching ratio. The latter can be estimated from the two products of branching ratios:

$$B(\bar{p}p \to \eta_{1420}\pi\pi)*B(\eta_{1420} \to \eta\pi\pi) \sim 3.3*10^{-3} \quad (2)$$

measured by CRYSTAL BARREL [4] and,

awaiting for the OBELIX datum,

$$B(\bar{p}p \to \eta_{1420}\pi\pi)*B(\eta_{1420} \to K\bar{K}\pi) \sim 2*10^{-3} \quad (3)$$

from an old bubble chamber experiment at CERN [1]. Assuming that $\eta\pi\pi$ and $K\bar{K}\pi$ almost saturate the $\eta(1420)$ decay, then $B(\eta_{1420} \to K\bar{K}\pi)$ is below 40% and the CELLO upper limit on $\Gamma(\eta_{1420} \to \gamma\gamma)$ becomes $\sim$ 3 KeV, which is about the value predicted by the Quark Model for a $q\bar{q}$ pseudoscalar [36]. With this upper limit on $\Gamma_{\gamma\gamma}$ the experimental ratio:

$$R_{\eta(1420)} = \frac{1}{3}\left(\frac{m_\pi}{m_{\eta(1420)}}\right)^3 \frac{\Gamma(\eta_{1420} \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} < 1.1 \quad (4)$$

can be expressed in terms of the $u\bar{u} - d\bar{d}, s\bar{s}$ and gg mixing parameters and the couplings to the neutral axial-vector current. Assuming dominance of singlet [42] or octet [43] admixture, the present limit sets to $<$ 13% the magnitude of $q\bar{q}$ mixing in $\eta(1420)$ against a model prediction of $\sim$ 8%.

On the theoretical side, warnings [44] to the use of specific model approximations arise from assuming a universal coupling constant to the neutral axial-vector current of octet and singlet, motivated from a straightforward generalization of the PCAC formula for $\pi^0 \to \gamma\gamma$ to derive the $\eta' \to \gamma\gamma$ decay amplitude. This is inconsistent with the picture of a non-conserved flavour singlet current even in the chiral limit because of the QCD axial anomaly. The consequence is that, from a rigorous chiral approach, the coupling strength of the singlet current includes an additional term for the two-photon coupling of glue, even without the assumption of existence of a "physical" glueball [44].

The experimental effort should be focused on the measurements of E/ι couplings to one and two photons, since radiative transition rates of $q\bar{q}$ states are easily calculable, and a glue-rich state would likely manifest an anomalous coupling. Moreover, radiative decays to $V\gamma$, with $V = \omega, \phi$, would allow identification of the dominant quark flavour component in a mixed $q\bar{q} - G$ state.

In the decay pattern of $\eta(1420)$ all recent experiments indicate a substantial fraction of direct three-body decay, both to $\eta\pi\pi$ and to $K\bar{K}\pi$. In isobar language the resonance decay proceeds via two L=0 pairs: the pion and the S-wave $\eta\pi$, or the kaon (pion) and the S-wave $K\pi$ ($K\bar{K}$) systems. This might constitute a strong argument in favour of a gluonic $\eta(1420)$ nature: both the low mass S-wave $\pi\pi$ ($K\pi$) system and the η meson seem strongly coupled to gg pairs, and the decay to $\eta(\pi\pi)_S$ should be enhanced for mesons built with valence gluons (glueballs, hybrids) [45]. It is very recent [46,47] the observation of a large decay rate of the scalar $f_0(1500)$ into two $(\pi^0\pi^0)_S$ pairs, apparently larger than the $f_0(1500) \to \pi^0\pi^0$ decay rate. Indeed, the $f_0(1500)$ is at present a strong candidate for the lighter scalar glueball [45]. From the analyses of CRYSTAL BARREL and OBELIX, deriving from (2) and (3) the value $\sim$ 0.6 for the ratio between the $\eta(1420)$ to $K\bar{K}\pi$ and $\eta(1420)$ to $\eta\pi\pi$ branching, it turns out that the two normalized direct three-body decay rates are comparable in magnitude ($\sim$ 30%).

The other two E/ι components, the $\eta(1460)$ and the $f_1(1420)$, would seem mostly $s\bar{s}$ objects because of their dominant $K^*\bar{K}$+c.c. decay mode. Due to the characteristics of their decay they are natural candidates for SU(3) singlet $q\bar{q}$ states. One would therefore expect copious production in kaon induced reactions, and typical $O(4-5)$ KeV two-gamma couplings. Results on K^-p induced reactions from SLAC [48] and BNL [32] are controversial, and, in the former, the evidence of $\eta(1460)$ and $f_1(1420)$ is not supported. The wide binning used by LASS [48] in its PWA of the $K^0_s K^\pm \pi^\mp$ system might cause hiding of the narrow $f_1(1420)$, whereas the $\eta(1460)$ intensity might be much weaker than the two dominant 1^+ components: the 1^{+-} $h_1(1380)$ and the 1^{++} $f_1(1510)$. The tiny two-gamma coupling predicted for $\eta(1460)$ is below expectation for a $q\bar{q}$ state, and an unusual pseudoscalar suppression should be invoked to explain it. On the contrary, $f_1(1420)$ exhibits a two-gamma width typical of nonet mesons.

5. CURRENT INTERPRETATIONS

The ground state of the pseudoscalar nonet is well established, its mixing angle deviates from the ideal value of $\sim$ 35°, indicating substantial mixing of the physical states with the SU(3) octet and singlet I=0 components. The established members of the first radially excited nonet (2^1S_0) are: I=1 $\pi(1300)$, I=1/2 $K(1460)$, and I=0 $\eta(1295)$, the latter being mostly non-$s\bar{s}$. The $\eta(1420)$ and the $\eta(1460)$ are natural candidates for the I=0 $s\bar{s}$ member of this nonet, even though their masses are below the Quark Model prediction of 1540 MeV [49]. The $\eta(1460)$ has high rating for being the missing member because of a sizeable strangeness component which characterizes its decay mode. Its vanishing two-gamma width, compared to expectations for the radial excitation of η', might be an indication of certain flavour singlet-octet mixing in the excited nonet, like in the ground state. The non observation of $\eta(1295)$ in untagged $\gamma\gamma$ events supports this argument.

In this scenario the $\eta(1420)$ would be an extra state, and therefore candidate for a hybrid meson or a glueball.

According to the flux tube [50] and constituent gluon [51,52] models hybrids should be rather heavy (>2 GeV) and broad (>300 MeV) objects, with a characteristic two-body decay mode to $L = 0$ plus $L = 1$ meson pairs [53]. Their spectrum seems therefore to lie outside the E/ι mass region of interest. Nevertheless, an enigmatic 0^{-+} signal has been observed by the VES collaboration below 2 GeV, with decay characteristics in agreement with expectations for an exotic hybrid [54].

Both lattice and sum rule calculations place the ground state 0^{-+} glueball near the 2^{++}, at a mass above 2 GeV [55,56]. The degree of accuracy reached by this type of calculations casts serious doubts on the appearance of a 0^{-+} glueball at the mass of the $\eta(1420)$. However, the abundant production of $\eta(1420)$ in J/ψ radiative decays and its weak coupling to photons strengthens the gluon-rich interpretation.

Moreover, if $\bar{p}p$ reactions at rest provide the opportunity to create a multi-gluon environment through dominance of quark annihilation over rearrangement, then the recent observations at Lear [4,9] constitute another supporting argument. In flight the lack of evidence of $\eta(1420)$ would seem to imply an inversion of the dominant mechanism, with quark rearrangement more effective than annihilation. This is, incidentally, a plausible explanation for the observed stronger violation of the OZI rule in $\bar{p}p$ annihilations at rest than in flight [57].

Finally, the observation of a strong coupling of $\eta(1420)$ to the $\eta\sigma$ system (where σ is the $\pi\pi$ S-wave amplitude) reinforces the gluonic interpretation [45]. The question then remains on how to link the experimental observation to the theoretical prediction of a 0^{-+} (quenched) glueball at a mass above 2 GeV.

Using measured radiative J/ψ production rates and two-gamma partial widths theorists can predict, in a model dependent way, the gluonic content of an isosinglet meson [23,58]. To what extent flavour mixing affects the predicted glueball mass spectrum is, however, presently unknown.

The situation with the axial vector mesons is also emblematic. The 1^{++} component of the E/ι structure, the $f_1(1420)$, is one of the candidates, together with the $f_1(1285)$ and the $f_1(1510)$, for the isosinglet members of the ground state $^3P_1$ nonet. The Quark Model would require only two candidates. The $f_1(1285)$ is the octet member of the nonet because of its dominant $\eta\pi\pi$ decay mode. However the observation of the radiative decay $f_1(1285) \to \phi\gamma$ [59] implies non-ideal mixing of the $^3P_1$ nonet. This leaves the $f_1(1420)$ and the $f_1(1510)$ for the singlet member. They both have a common $K^*\bar{K}$ decay mode, but while $f_1(1510)$ is abundant in kaon induced reactions [48], $f_1(1420)$ seems mostly produced via non-strange quarks [32]. The fact that they have never been observed at one in a single experiment has for long suggested certain caution as to whether the two states are indeed distinct [60]. If they are genuine resonances, then one of them is an exotic, because it is unexpected for two narrow mesons with the same J^{PC} to be so close in mass. Despite the lack of evidence in $\gamma\gamma$ collisions, the $f_1(1510)$ would likely be the singlet $^3P_1$, because its mass is closer to the Quark Model prediction and because strangeness strongly characterizes both its production and decay. With the $f_1(1510)$ completing the 1^{++} nonet the GMO quadratic mass formula predicts a mixing angle of $\sim 62°$ [61].

Experimental observations suggest for the $f_1(1420)$ a dominant quarkonium nature because of its large two-gamma coupling. Its branching ratio into $K\bar{K}\pi$ is larger than that of $f_1(1285)$ in pp central collisions [62], and comparable in $\gamma\gamma$ collisions [17,18,20]. Flavour mixing seems responsible for its enhanced $K^*\bar{K}$ (but not $\phi\gamma$ [59]) decay and for its abundance in J/ψ hadronic decay recoiling against the ω (but not against the ϕ) [24]. Besides certain puzzling properties deriving from its quarkonium nature, nothing seems to indicate a significative gluonic component in the $f_1(1420)$, apart from its observation in J/ψ radiative decays [10]. Mixing with the lightest axial vector glueball is unlikely because the latter is expected at $\sim$ 4 GeV [55].

What is then the nature of the $f_1(1420)$? It has been proposed as a $K^*\bar{K}$ molecule or a 4-quark state. The two interpretations have however strong analogies. A $q^2\bar{q}^2$ system is thought as a color-singlet hadronic cluster, characterized by a typical "fall-apart" decay mechanism into a two-hadron system with a rest mass below the cluster mass [63]. A molecule is a novel feature of a multiquark system considered as the bound state of two color-singlet $q\bar{q}$ mesons [64,50]. Multiquark hadronic clusters are predicted to have masses well above 2 GeV, since they appear to favour participation of heavy quarks [66]. Since the $f_1(1420)$ is just above the $K^*\bar{K}$ threshold it has been proposed as an S-wave non-resonant threshold enhancement rather than a weakly bound molecular system [67]. The weak phase motion observed by E771 [32] seems to support the non-resonant interpretation. More recently both Longacre [68] and Swanson [69] have proposed models which are able to fit existing experimental distributions without the specific need to introduce an axial vector resonance at 1420 MeV. Additional tests to distinguish between the molecular and the non-resonant nature of the $f_1(1420)$ have been proposed by Barnes [35].

6. CONCLUSIONS

Although the theory is manifestly inadequate to explain all observed phenomena concerning the E/ι spectroscopy, it is nevertheless necessary to emphasize that there is still room, at present, for new experimental initiative, as stressed throughout this report. Besides exploring other decay channels, new information might come from a multichannel analysis of the $\eta(1420)$ observed decay modes in a unitarized approach. The argument is more general and concerns all resonances coupling to multiple final states. The simultaneous fit of several data sample with different forms of the dynamical amplitude (Breit-Wigner) and appropriate decay form factors could disentangle mass degeneracy of resonances with equal J^{PC}, resolve the effect of threshold openings and accomodate all observed masses and decay partial widths [70]. The effort might be worthwhile, at least, to confirm the pattern of states in the E/ι mass region. To emphasize that there is still matter to debate and that the game is not at all over, we conclude by recalling a recent more exotic explanation of the pseudoscalar $\eta(1420)$ nature in terms of SUSY *s*particles [71].

REFERENCES

1. P. Baillon et al., Nuovo Cimento 50 A (1967) 393.
2. F. Nichitiu, Proc. HADRON 95 (World Sci., 1995; eds. M. Birse et al.) 408.
3. Yu.D. Prokoshkin, S.A. Sadovsky (GAMS Coll.), contribution to LEAP 96.
4. C. Amsler et al. (Crystal Barrel Coll.), Phys. Lett. B 358 (1995) 389.
5. C. Defoix et al., Nucl. Phys. B 44 (1972) 125.
6. A. Ando et al., Phys. Rev. Lett. 57 (1986) 1296.
7. G. Gutierrez et al. (E690 Coll.), Proc. HADRON 95 (World Sci., 1995; eds. M. Birse et al.) 408.
8. J.Z. Bai et al. (BES Coll.), Prep. BIHEP-EP1 95-04.
9. A. Bertin et al. (Obelix Coll.), Phys. Lett. B 361 (1995) 187.
10. J.Z. Bai et al. (MARK III Coll.), Phys. Rev. Lett. 65 (1990) 2507.
11. J.E. Augustin et al. (DM2 Coll.), Phys. Rev. D 42 (1990) 10.
12. J.E. Augustin et al. (DM2 Coll.), Phys. Rev. D 46 (1992) 1951.

13. D.V. Bugg et al., Phys. Lett. B 353 (1995) 378.
14. A. Bertin et al. (Obelix Coll.), in preparation.
15. B. Lorstad et al., Nucl. Phys. B 14 (1969) 63.
16. M. Aguilar-Benitez et al., Nucl. Phys. B 14 (1969) 195.
17. H. Aihara et al. (TPC/2γ Coll.), Phys. Rev. D 38 (1988) 1.
18. P. Hill et al. (JADE Coll.), Z. Phys. C 42 (1989) 355.
19. H.J. Behrend et al. (CELLO Coll.), Z. Phys. C 42 (1989) 367.
20. G. Gidal et al. (MARK II Coll.), Phys. Rev. Lett. 59 (1988) 2016.
21. T.A. Armstrong et al. (WA76 Coll.) Z. Phys. C 52 (1991) 389.
22. C.N. Yang, Phys. Rev. D 77 (1950) 242.
23. M.B. Cakir and G. Farrar, Phys. Rev. D 50 (1994) 3268.
24. L. Kopke and N. Wermes, Phys. Rep. 174 (1989) 67.
25. K.D. Duck et al. (Asterix Coll.), Z. Phys. C 45 (1989) 223.
26. H. Genz, Phys. Rev. D 28 (1983) 1094.
27. H. Genz, Phys. Rev. D 31 (1985) 1136.
28. C. Amsler, Zurich report UZH-PH-100/93 (1993).
29. L. Adiels et al., Z. Phys. C 35 (1987) 15.
30. C. Amsler et al. (Crystal Barrel Coll.), Z. Phys. C 58 (1993) 175.
31. F. Gilman and R. Kauffman, Phys. Rev. D 36 (1987) 2761.
32. Z.Bar-Yam et al. (E771 Coll.), Proc. HADRON 91 (World Sci., 1992; eds. S. Oneda and D.C. Peaslee) 61.
33. M.G. Rath et al. (E769 Coll.), Phys. Rev. D 40 (1989) 693.
34. F.E. Close, Proc. XXVII Int. Conf. on HEP, Glasgow, UK (IOP Pub., 1994; eds. P. Bussey and I. Knowles).
35. T. Barnes, Proc. NATO ASI on Hadron Spectroscopy and the Confinement Problem, London (UK) (Plenum Press 1996; eds. D.V. Bugg) 37.
36. M.R. Pennington, Univeristy of Durham report DTP-90/68 (1990).
37. B. Bagchi and S. Basu, MC-TH 87-18 (1987).
38. T. Teshima and S. Oneda, CHUBU 87-5 (1987).
39. H. Genz, M. Nowakowski and D. Woitschitzky, TKP 90-9 (1990).
40. M.L. Nekrasov, HEP-PH-9503405 (1995).
41. S. Iwao, SCAN 9605174 (1996).
42. J. Bartelski and S. Tatur, NCAC 246 (1992).
43. I. Kitamura, N. Morisita and T. Teshima, Nuovo Cimento 107 A (1994) 2429.
44. G.M. Shore and G. Veneziano, Nucl. Phys. B 381 (1992) 3.
45. C. Amsler and F.E. Close, Phys. Lett. B 353 (1995) 385; Phys. Rev. D 53 (1996) 295.
46. S. Resag et al. (Crystal Barrel Coll.), Proc. HADRON 95 (World Sci., 1995; eds. M. Birse et al.) 374.
47. U. Thoma et al. (Crystal Barrel Coll.), contribution to LEAP 96.
48. D. Aston et al. (LASS Coll.), Phys. Lett. B 201 (1988) 573.
49. S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189.
50. N. Isgur, R. Kokosky and J. Paton, Phys. Rev. Lett. 54 (1985) 869.
51. F. Iddir et al., Phys. Lett. B 205 (1988) 564.
52. S. Ishida et al., Phys. Rev. D 47 (1992) 179.
53. F.E. Close and P.R.Page, Nucl. Phys. B 443 (1995) 233.
54. D. Ryabchikov et al. (VES Coll.), Proc. HADRON 95 (World Sci., 1995; eds. M. Birse et al.) 192.
55. G. Bali et al. (UKQCD Coll.), Phys. Lett. B 309 (1993) 378.
56. D. Weingarten, Nucl. Phys. B (Proc. Suppl.) 34 (1994) 29.
57. V. Lucherini, invited talk to LEAP 96.
58. F.E. Close, G.R. Farrar and Z. Li, HEP-PH/9610280, RAL-96-052, RU-96-35 (1996).
59. S.I. Bityukov et al., Phys. Lett. B 203 (1988) 327.
60. M. Faessler, Proc. NATO ASI on Hadron Spectroscopy and the Confinement Problem, London (UK) (Plenum Press 1996; eds. D.V. Bugg) 1.
61. A. Palano, Proc. NATO ASI on Hadron Spectroscopy and the Confinement Problem, London (UK) (Plenum Press 1996; eds. D.V. Bugg) 189.
62. T.A. Armstrong et al. (WA76 Coll.), Phys.

Lett. 221 (1989) 216.
63. R.L. Jaffe, Phys. Rev. Lett. 38 617E (1977) 195.
64. J. Weinstein and N. Isgur, Phys. Rev. Lett. 48 (1982) 659.
65. N. Isgur, Acta Physica Austriaca, Suppl. XXVII (1985) 177.
66. J.P. Ader et al., Phys. Rev. D 25 (1982) 2370.
67. D.O. Caldwell, Mod. Phys. Lett. A 2 (1987) 771.
68. R.S. Longacre, Phys. Rev. D 42 (1990) 874.
69. E.S. Swanson, Nuovo Cimento 107 A 11 (1994) 2367.
70. D.V. Bugg, Proc. NATO ASI on Hadron Spectroscopy and the Confinement Problem, London (UK) (Plenum Press 1996; eds. D.V. Bugg) 379.
71. G.R. Farrar, Phys. Rev. Lett., 76 (1996) 4111.