Exotics Searches

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Abstract

The experimental information on the search for non $q\bar{q}$ mesons as glueballs, hybrids and multiquark states is reviewed. Candidate states which are particularly amenable to detailed study by accumulating large samples of $J/\psi$, $\eta_c$, $\chi$ decays at a $\tau$-charm factory are discussed.

Invited talks to the 3rd Workshop on a $\tau$-charm factory

Marbella, Spain, June 1-6 1993
1. INTRODUCTION

The present understanding of strong interactions is that they are described by Quantum Chromo Dynamics (QCD). This non-Abelian field theory not only describes how quarks and antiquarks interact, but also predicts that the gluons which are the quanta of the field will themselves interact to form mesons. If the object formed is composed entirely of valence gluons (\(gg\) or \(ggg\)) the meson is called a glueball, however if it is composed of a mixture of valence quarks, antiquarks and gluons (i.e. \(q\bar{q}g\)) it is called a hybrid. In addition, \(q\bar{q}q\bar{q}\) states are also predicted. An unambiguous confirmation of these states would be an important test of QCD and would give fundamental information on the behaviour of this theory in the confinement region.

However, until large dedicated computers (QCD machines) are available, in order to compute QCD with sufficient precision, the spectrum of the hadrons will be only known in a qualitative way. The perturbative approach cannot, in fact, be easily extended to the low energy regime; the light hadron spectrum cannot be reliably calculated, and it is even more difficult to predict dynamical properties, such as decay widths. The spectroscopy of low-mass states can however be accounted for, to a large degree, by QCD-inspired models. The most complete of these, built by S. Godfrey and N. Isgur in 1985 [1], is able to describe with sufficient accuracy the \(q\bar{q}\) mesons spectrum from the pion to the \(\Upsilon\). This model is therefore often used in order to test whether a new discovered resonance belongs or not to one of the \(q\bar{q}\) multiplets.

Although the existence of a glueball spectrum is predicted by QCD, the extraction of reliable predictions for the masses of these states presents an important challenge. Recent advances in lattice gauge theory calculations [2] are however beginning to shed light on both ordering of states and mass scale, giving values of \(1550 \pm 50 \text{ MeV}\) and of \(2270 \pm 100 \text{ MeV}\) for the lowest-lying \(0^{++}\) and \(2^{++}\) glueballs. While the absolute scale is still uncertain, the mass ratio prediction is in line with previous values from various other theoretical models (MIT bag model, potential models, QCD sum rules, flux-tube model) [3].

The mesonic decay of glueballs is determined by their flavor SU(3) singlet nature; ignoring phase space factors, glueballs are naively expected to couple equally to all flavors, while arguments from perturbation theory [4] favor a stronger coupling to strange, rather than to u- or d-quarks. It is in any case important to note that these production and decay characteristics rest on the assumption of pure gluonium states, and may be considerably modified by an admixture of \(q\bar{q}\) states.

2. THE SEARCH FOR NON \(\bar{q}q\) STATES

The experimental search for gluonium states started in 1980 with the discovery, by Mark II [5] and the Crystal Ball [6] experiments at SPEAR of a large \(\Upsilon/\eta(1440)\) signal \((m=1440 \text{ MeV}, \Gamma=50 \text{ MeV})\) in the radiative \(J/\psi\) decay \(J/\psi \rightarrow \gamma K\bar{K}\pi\) (see fig. 1). The quantum numbers of this state have been determined by the Crystal Ball experiment to be \(J^{PC} = 0^{-+}\). Since the pseudoscalar net was already full and since the radiative \(J/\psi\) decay was understood to proceed through a two gluon intermediate state as shown in fig. 2a), the
new resonance was readily proposed as the first candidate for being a glueonium state.

This finding and the discovery of the $\theta(1720)$ by the Crystal Ball in the reaction $J/\psi \rightarrow \gamma \eta \eta$, motivated a new interest in meson spectroscopy so that the search for gluonic mesons has been the main motivation of light meson spectroscopy over the last years. However, up to now the results obtained by the different experiments are rather ambiguous. This is mostly due to the complexity of the hadron spectrum, where $q\bar{q}$ ground states overlap, in the same mass region, with radial excitations so that, after some initial enthusiasm, it now seems unlikely that one single experiment could discover gluonium states. The evidence for these non-$q\bar{q}$ mesons can, in fact, only come from the comparison of light meson spectroscopy from several dynamical sources, i.e. $J/\psi$ radiative and hadronic decays, $\pi$ or $K$ induced peripheral reactions, $p\bar{p}$ annihilation, $\gamma \gamma$ collisions, central production etc.

What characteristics are there which may help in disentangling glueballs from quarkonium states?

- a) Glueballs are flavour SU(3) singlets, so they have isospin zero and are expected to couple, apart for phase space factors, equally to final states of all flavours.
- b) Mesons are grouped into nonets with the same $J^{PC}$. The finding of extra states having quantum numbers of an already completed nonet could be a signal for having found an exotic state. However, the undefined situation of radial excitations and multiquark states does not allow an easy classification of newly discovered resonances.
- c) Glueballs and hybrids can have unusual production or decay characteristics.

Figure 1: Observation of the $\iota/\eta(1440)$ by: a,b) MarkII and c) Crystal Ball
Figure 2: Diagrams describing a) \(J/\psi\) radiative decay, b) \(J/\psi\) hadronic decays, c) \(\gamma\gamma\) collisions.

- d) Glueballs and hybrids can have any \(J^{PC}\) combination but some of them (like \(0^{-+},\ 0^{--},\ 1^{-+},\ ...\)) are not allowed for \(q\bar{q}\) states. The finding of one of these states would be the best evidence for the existence of gluonic mesons.

- e) Since gluons do not carry electric charge, glueballs should not couple to \(\gamma\)'s. A new parameter has been introduced to quantify this idea, the ”stickiness” [8]:

\[
S = \frac{\Gamma(J/\psi \rightarrow \gamma X) \times PS(\gamma\gamma \rightarrow X)}{PS(J/\psi \rightarrow \gamma X) \times \Gamma(\gamma\gamma \rightarrow X)}
\]

This definition implies that \(S\) should be large for glueballs which means that they should have large branching ratios in ”gluon rich” channels like radiative \(J/\psi\) decay and small \(\gamma\gamma\) widths.

In conclusion, the strategy developed over the last years for finding exotic mesons is based essentially on the following ideas:

- i) Compare meson spectroscopy from different production mechanisms;
- ii) Make use of reactions which can ”tag” the flavour content or the quantum numbers of the produced resonance.

As an example of i) it is interesting to compare the \(\eta\pi\pi\) mass spectrum from radiative \(J/\psi\) decay [9] (fig. 3a)) with that from central hadronic collisions in the reaction \(pp \rightarrow p(\eta\pi\pi)p\) [10] (fig. 3b)). In radiative \(J/\psi\) decay we observe a large production of pseudoscalars, visible by the strong enhancement in the \(\eta'\) region. In central production, on the other hand, axial vectors (evidenced by the strong \(f_1(1285)\) signal) are seen to be enhanced with respect to pseudoscalars.

As an example of ii) and how \(\gamma\gamma\) collisions selected in two different kinematic ranges are able to discriminate between different spin assignments for the produced final states,
we show in fig. 3 the \( \eta \pi \pi \) mass spectrum for "no tag" events, when the \( Q^2 \) of the reaction sketched in fig. c) is so small that the two \( \gamma \)'s are real and scattered electrons are not detectable because they are lost in the beam pipe. Fig. 4b), on the other hand, shows the same \( \eta \pi \pi \) mass spectrum when one of the electrons is detected so that the \( Q^2 \) is relatively high and one of the two \( \gamma \) is not real. We observe the presence of the \( \eta' \) in both spectra but the spin-one resonance \( f_1(1285) \) is visible only in the reaction \( \gamma \gamma^* \rightarrow \eta \pi \pi \). The Yang-Landau theorem states that two massless spin-one objects cannot combine to form a spin-one object; thus, when a resonance is not seen in the fusion of two real photons, but is observed when one of the photons is far from the mass shell, it indicates that the resonance is probably spin-one.

3. THE 0\(^{-}\)\( ^{+}\), 0\(^{++}\), 1\(^{++}\) AND 2\(^{++}\) MULTIPLETS

In the framework of the quark model, quark and anti-quark combine to multiplets with well defined values of \( J^{PC} \). States with an angular momentum of \( L=1 \) between quark and anti-quark in a spin-triplet state populate the \( ^3P_0 \ (0^{++}) \), \( ^3P_1 \ (1^{++}) \) and \( ^3P_2 \ (2^{++}) \) multiplets; those with \( L=0 \) and the quark and anti-quark in a spin singlet state populate the \( ^1S_0 \ (0^{-+}) \) multiplet. Even without assigning observed states to a given multiplet, the existence of non-\( \bar{q}q \) states which lie in the same mass range and have identical quantum numbers to those of these multiplets can be established by the simple presence of more low-mass states than predicted by the quark model. Using the Godfrey-Isgur model as a guide, one can tentatively assign the states listed in Table I with those making up the 0\(^{-}\), 0\(^{++}\), 1\(^{++}\) and 2\(^{++}\) multiplets, although such an assignment is not necessarily unique. The numbers in square brackets are
Figure 4: a) $\eta\pi\pi$ effective mass from $\gamma\gamma \to \eta\pi\pi$, b) $\eta\pi\pi$ mass distribution from $\gamma\gamma^* \to \eta\pi\pi$. The data are from MarkII.

the Godfrey-Isgur predictions for each state.

| $J^P C$ | $l=1$       | $l=0$       | $l=1/2$      |
|---------|-------------|-------------|-------------|
| 0$^{--}$| $\pi(140)$  | $\eta(547)$ | $K(494)$    |
|         | [150]       | [520], [960]| [470]       |
| 0$^{++}$| $a_0(980)$  | $f_0(975)$  | $K_0^*(1430)$ |
|         | [1090]      | [1090], [1360]| [1240]     |
| 1$^{++}$| $a_1(1260)$ | $f_1(1285)$ | $K_{1A}^*$   |
|         | [1240]      | [1240], [1480]| [1380]     |
| 2$^{++}$| $a_2(1320)$ | $f_2(1270)$ | $K_2^*(1430)$ |
|         | [1310]      | [1280], [1530]| [1430]     |

In this assignment, most $J^{++}$ states lie in the 1.3 GeV to 1.5 GeV mass region, with a relatively small L-S splitting. A notable exception are the $I=0$ and $I=1$ 0$^{++}$ states $f_0(975)$ and $a_0(980)$, which also exhibit the largest mass differences to the Godfrey-Isgur model predictions.

4. 0$^{++}$ NON-$\bar{q}q$ CANDIDATE STATES

Given the ambiguities in the assignments to the 0$^{++}$ nonet and the discrepancies between the experimental states and the Godfrey-Isgur predictions for this nonet, it is natural to

1) The $K_{1A}$ and the corresponding $1^{+-}$ state $K_{1B}$ are nearly $45^\circ$ mixed states of the $K_1(1270)$ and $K_1(1400)$. 

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consider alternative assignments in which the isoscalar and isovector $0^{++}$ states are identified with some of the less-well determined resonances in the 1.3 – 1.5 GeV region. A consequence is that the $f_0(975)$ might then be a weakly bound $K\bar{K}$ system or of other non-qq origin. Information on this region has been obtained by D. Morgan and M.R. Pennington [13]. They have combined data on $f_0(975)$ production in $J/\psi$ and $D_s$ decays with information obtained from central production and elastic $\pi\pi$ and $K\bar{K}$ processes. Fig. 5 shows the projection of their fits on the available data from Mark III and DM2 assuming one (as for a $K\bar{K}$ molecule) or two (as for a quark model state) poles. In addition to concluding that the $f_0(975)$ is most probably not a $K\bar{K}$ molecule but that it has a conventional Breit-Wigner structure with a rather narrow width ($\Gamma_0 \sim 52$ MeV) and comparable couplings to $\pi\pi$ and $K\bar{K}$, they argue the existence of an additional, very broad $f_0(1000)$ which would play the role of the lightest broad I=0 scalar. Rather than reducing the ambiguities in the scalar sector however, this increases the number of scalar states below 1800 MeV, since the existence of a broad scalar structure around 1400 MeV seems experimentally well established thanks to recent observations of its decay to $\rho\rho$ [14], $\pi^0\pi^0$ and $\eta\eta$ [15]. A similar conclusion on the $f_0(975)$ is drawn from the study of centrally produced $\pi\pi$ and $K\bar{K}$ final states but with slightly different parameters ($\Gamma_0 = 72 \pm 8$ MeV, $g_K/g_\pi = 2.0 \pm 0.9$) [16].

Figure 5: DM2 and MARK III data on $J/\psi \rightarrow \phi\pi^+\pi^-, \phi K^+K^-$. The fits with 1) one pole, 2) two poles are described in [13].

On the other hand, new results from BES [17] detecting the $f_0$ recoiling against $\omega$ and against $\phi$ in $J/\psi$ decay favor the molecular interpretation: determining the relative decay ratios of $J/\psi \rightarrow \phi f_0(975)$ to $J/\psi \rightarrow \omega f_0(975)$, they find a value of $2.2^{+3.3}_{-0.8}$, consistent with the
molecular state expectation $^{18}$ of $\text{BR}(J/\psi \to \phi f_0(975)) = 2 \cdot \text{BR}(J/\psi \to \omega f_0(975))$. They also determine a width $\Gamma_{\pi\pi} = 36 \pm 11$ MeV for $f_0(975)$, which is in good agreement with the expected value $^{19}$ of $\sim 38$ MeV for a KK molecular state.

The case for a molecular interpretation of the $f_0(975)$ might be bolstered by unambiguous evidence for further molecular states. One promising state in this context is $\psi(4040)$ which has been considered a candidate for a $D^*\bar{D}^*$ molecule. Since molecular states would be weakly bound, the decay pattern should follow that of the quasi-free constituents, giving an easily testable prediction for the decay branching ratios $^{20}$. Another experimental test is a determination of the couplings of $a_0$ and $f_0$ to $\gamma\gamma$, which are predicted to be small and equal in the molecular picture (with a large coupling to $\bar{K}K$) $^{19}$.

The existence of radial excitations of the $\bar{q}q$ states increases the number of low mass states with a given $J^{PC}$. The first radial excitation of the $^3P_0$ partner of the $0^{++}$ ground state $K^*_0(1430)$ has been observed in Kp scattering by LASS at a mass of 1.95 GeV, and with a width of 200 MeV $^{21}$. The same experiment has also measured the first radial excitation of the $2^{++}$ $K^*_2(1430)$ at a mass of 1.97 GeV and a width of 370 MeV in the process $K^-p \to K^0\pi^+\pi^-n$ $^{21}$. Similarly, the first radial excitation of the $f_2(1270)$, possibly observed in $^{22}$ with a mass of $(1799 \pm 15)$ MeV has a large width of $(280 \pm 40)$ MeV. The general tendency of large widths and a mass split of $\sim 500$ MeV between the ground states and their first radial excitation is also consistent with the predictions of the Godfrey-Isgur model. In particular, the first radial excitations in the $0^{++}$ and $2^{++}$ nonets, the $2^3P_0$ and $2^3P_2$ states, are predicted to lie at 1780 MeV, resp. 1820 MeV.

Figure 6: $\pi^+\pi^-$ (Mark II), $\pi^0\pi^0$ (Crystal Ball), $K_S^0K_S^0$ (CELLO/PLUTO) and $K^+K^-$ (ARGUS) invariant mass distributions from $\gamma\gamma$ collisions $^{24}$.)

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If the $f_0(975)$ is not the lowest lying $0^{++}$ state, its place in the $0^{++}$ nonet must be filled by some other (qq) state. The mass region 1.3 – 1.6 GeV contains several more or less well established candidate states; this mass window is however somewhat higher than the prediction from the model of Godfrey and Isgur.

There are indications from LASS of an S-wave structure at 1.53 GeV in $K^- p \rightarrow K_S^0 K_S^0 \Lambda$ [25], which would be naturally interpreted as the $^3P_0$ ground state partner of the $f_2'(1525)$. Indications of the corresponding iso-vector state have been seen in its neutral mode in $\eta \pi^0$ by GAMS [26], as well as in its charged mode in $\eta \pi^-$ by Benkei [27] at about 1.3 GeV in $\pi p \rightarrow \pi \eta n$ (Fig. 7). It should be noted that in spite of larger statistics, VES sees no activity around 1.3 GeV in the S-wave in a partial wave analysis of the $\eta \pi^-$ system produced in $\pi N$ scattering at 37 GeV/c [28]. The fact that these states would be mass-degenerate with $f_2(1530)$ and $a_2(1320)$, together with the relatively low statistical significance of the signals, gives rise to the worry of feedthrough from the partial wave analyses; confirmation is needed for both states. An I=1 $0^{++}$ state $a_0(1430 \ldots 1480)$ with a width of 230 \ldots 270 MeV has been observed by the Crystal Barrel collaboration [29] in the process $\bar{p} p \rightarrow \eta \pi^0 \pi^0$; further study is needed, but it would be important to ascertain whether this state could be the first radial excitation or the $^3P_0$ ground state itself. In both cases, this state could set the mass region of the $0^{++}$ nonet.

Recently, a very broad $(4\pi)^0$ enhancement has been seen in nucleon-antinucleon annihilation into five pions by two groups [14]. In both cases, a dominant decay mode of this I=0 $0^{++}$ object is $\rho \rho$, although it is also observed in $\pi^0 \pi^0$, $\eta \eta$ [15] and $\sigma \sigma$. The mass (1374 ±
38 MeV) and width (375 ± 61 MeV) of this state are compatible with the f_0(1400), but its decay modes – which are those expected for a (u\bar{u} + d\bar{d}) state in the same nonet as K^*_0(1430) – are not; here too, further study is needed.

Two states with J^{PC} = 0^{++} lie in the 1500 - 1600 MeV mass region. The state G(1590), first observed by the GAMS experiment in the process π^-p → ηηn and ηη'n [30], has unusual decay properties, in that its decay rate into ηη' is three times larger than its ηη decay, and in that it has not been seen in K\bar{K}. An upper limit for BR(G(1590) → π^0π^0) of less than 0.3 × BR(G(1590) → ηη) is also found [30].

The Crystal Barrel group has observed a 0^{++} state [29] with a mass of 1520 ± 45 MeV and a width of 148 ± 25 MeV decaying into π^0π^0 and ηη in pp annihilation at rest (Fig. 8). At the same time, they give an upper limit for the ratio of decay ratios of a state around 1550 MeV into ηη' and into ηη of less than 0.2 [29]. No indications for a scalar state in the same

Figure 8: a) Dalitz plot for 3π^0 events from Crystal Barrel. b) π^0π^0 invariant mass distribution (the solid line corresponds to a preliminary fit containing the f_0(1515)). The scalar amplitude f_0(1515) corresponds to the narrow bands that cross the Dalitz plot at ~ 2.3 GeV^2. c) ηη effective mass from \bar{p}p → π^0ηη

mass region of ~ 1550 MeV come from radiative J/ψ decay [31], nor central production [32],

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while a weak signal around 1.5 GeV is seen in the S-wave in Kp scattering \[25\], which would speak against a glueball interpretation. On the other hand, QCD sum rules predict a suppression by one order of magnitude for scalar glueballs relative to tensor glueballs \[33\], so that given the available statistics, non-observation in J/\(\psi\) radiative decays would not be surprising.

Assuming the above assignment of \(f_0(1400)\), \(f_0(1520)\) could then only be assigned to the ninth member of the 0\(^{++}\) nonet, mostly \(s\bar{s}\), which would however contradict the observed strong coupling to \(\pi\pi\), as well as the weakness of this state in Kp scattering. If the Crystal Barrel \(f_0(1520)\) is identified with the GAMS \(f_0(1590)\), then the two experiments are in contradiction with respect to the \(\eta\eta'\) and \(\pi^0\pi^0\) decay modes. If on the other hand, the GAMS \(f_0(1590)\) decay to \(\eta\eta'\) really is dominant, then there is an excess of 0\(^{++}\) states around 1500 MeV. The conclusion that one may be a non-\(\bar{q}q\) state, or that the \(f_0(1520)\) and \(f_0(1590)\) are mixed states of a glueball and the ninth member of the \(q\bar{q}\) nonet is tempting. In this respect, the absence of a signal for either state in \(\pi^0\pi^0\) in \(\gamma\gamma\) collisions \[24\] is significant. A second possibility would be that of identifying \(f_0(1520)\) with the first radial excitation, i.e. the 2\(^{3}\)P\(_0\) state; however, its relatively narrow width of 148 \(\pm\) 25 MeV speaks against this possibility. While the search for further decay modes of the \(f_0(1500)\) and/or \(f_0(1590)\) will help in clarifying their nature, a high statistics search for either state in J/\(\psi\) radiative decay, as well as a clarification of the nature of the \(f_0(975)\), would clearly be of great importance to establish their glue content.

Figure 9: Evidence for the G(1590) from GAMS. a) \(\eta\eta\) invariant mass distribution. b) S-wave contribution from a partial wave analysis of the \(\eta\eta\) invariant mass distribution. c) \(\eta\eta'\) invariant mass distribution. The dashed line is the phase space normalized to the number of events in the measured mass interval, the full line a Breit-Wigner fit \[30\].
5. **2++ NON-qq CANDIDATE STATES**

The state $\theta(1720)$ has been of considerable interest since its discovery by Crystal Ball through the process $J/\psi \rightarrow \gamma \theta, \theta \rightarrow \eta\eta$, and its subsequent confirmation by MARK III and DM2 (in radiative $J/\psi$ decays), as well as by fixed target experiments ($\Omega$-WA76). Its $J^{PC}$, originally determined to be $2^{++}$ was later revised to $0^{++}$ by MARK III [31]. Recent $J^{PC}$ determinations in central production and $J/\psi$ radiative decay [34, 17] however again favor a $2^{++}$ assignment. Fig. 10 shows the signal and decay angular distribution of $\theta(1720)$ in central production; both $f_2(1525)$ and $\theta(1720)$ are well described by a $2^+$ angular distribution. An analysis by BES of the processes $J/\psi \rightarrow \omega K^+K^-$ and $J/\psi \rightarrow \gamma \pi^0\pi^0$ gives a dominance of $2^{++}$ in this mass region, but allows for a $0^{++}$ component on the high mass side (around 1750 MeV) in the spin analysis of the reaction $J/\psi \rightarrow \gamma K^+K^-$. Assuming the $2^{++}$ assignment is correct, then $\theta$ cannot be the $s\bar{s}$ member of the $2^{++}$ nonet (a role fulfilled by $f_2'(1525)$), but is too light to be a radial excitation. Several other properties also make the $\theta(1720)$ a rather unique state. Although the $\theta$ decays predominantly to $K\bar{K}$ [35] (and to a lesser degree to $\pi\pi$ and $\eta\eta$), it is not produced in $Kp$ scattering [25], and is produced at a much larger rate in radiative $J/\psi$ decay than the $s\bar{s} f_2'(1525)$ [36]. This is also seen in central production where the $t$ distribution for $f_2'(1525)$ and $\theta(1720)$ are quite different [34].

The comparison of $J/\psi$ decays into $\omega+X$ and $\phi+X$ allows a determination of the quark content of the resonance $X$. In the approximation of ideal mixing, a state $X$ recoiling against
an $\omega$ will consist of $u$ and $d$ quarks, while a state recoiling against a $\phi$ contains strange quarks. A clear signal for $\theta$ is seen in $K^+K^-$ recoiling against $\omega$. However, the $K^+K^-$ spectrum recoiling against a $\phi$ shows the expected presence of $f_2'(15252)$ but it is not clear if the shoulder visible in the 1.65 region can be attributed to the presence of the $\theta(1720)$.

Although many states are expected in the 2 GeV region, several structures seen around 2.2 GeV in radiative $J/\psi$ decays are remarkable by their unexpectedly narrow width (smaller than the experimental resolutions of $\sim$ 100 MeV); with $0^{++}$ glueball candidates around 1.5 GeV setting the mass scale, a $2^{++}$ glueball is expected in this mass region. A narrow state at 2.23 GeV, first seen by MARK III in radiative $J/\psi$ decay to $K^+K^-$ and $K_S K_S$ [37], has been recently confirmed by BES [17], which has also observed this state in the process $J/\psi \rightarrow \gamma\eta\eta$. A spin-parity analysis by MARK III gives $J \geq 2$, while $J^{PC}$ must lie in the series (even)$^{++}$ due to the observation in $K_S K_S$. A weak structure at 2.22 GeV is also seen in $\pi^- p$ scattering in $\eta\eta'$. A lower limit $J \geq 2$ is obtained from anisotropic angular distributions. In view of the strange quark content of $\eta$ and $\eta'$, it is tempting to identify this structure with the $\xi(2230)$ above. A spin-parity analysis of the signal seen at BES is in progress, but may be limited by statistics as well as detector acceptance. This analysis might be able to differentiate between spin 0 and 2, but will most likely not be able to test the suggestion that $\xi$ is the $4^{++}$ $s\bar{s}$ partner of the $f_4(2030)$ [38], as suggested by an analysis of LASS data which finds a a $4^{++}$ resonance at 2.209 GeV in the process $K^- p \rightarrow K_S K_S \Lambda$ [25]. A possibly different state at the

Figure 11: a) $K_S K_S$ and $\eta \eta$ invariant mass from radiative $J/\psi$ decay from BES. b) $\phi \phi$ invariant mass from radiative $J/\psi$ decay from MARK III (efficiency-corrected spectrum with fits to Breit-Wigner resonances). c) Cross section for the process $\bar{p} p \rightarrow K_S K_S$. 

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same mass and with a comparable width is seen in radiative J/ψ decay to φφ by MARK III and DM2 [13]. It is interesting to note that while spin-parity analyses of both experiments suggest a pseudoscalar assignment for this state, spin-parity analyses of a φφ resonance in the same mass region in hadronic production [10] are consistent with J^P = 2^+. In view of ω − ϕ mixing, it is natural to complement the study of this state by a search in the processes J/ψ → ωφ and J/ψ → ωω. The former in particular would be interesting as it could be an indication for a (u̅u + d̅d)g hybrid; such a hybrid with J^PC = 2^{++} is predicted at 2.32 GeV [4].

It is all the more intriguing that no evidence for either state has been found in a ¯pp formation experiment. In none of the reactions ¯pp → K^+K^−, ¯pp → K_SK_S or ¯pp → φφ is there an indication of resonant behaviour in the 2.2 GeV region [41]. Fig. 11 shows the measured cross-section for ¯pp → K_SK_S.

6. PSEUDOSCALARS

After the initial discovery of the ι/η(1440) signal in J/ψ radiative decay several experiments looked to the 1.4 GeV mass region in a variety of different reactions, from p̅p annihilations to π or K induced reactions, from central production to γγ collisions. However, the striking complication appeared that in the E/ι mass region the number of states which contributed to the enhancement observed in the mass spectrum changed from one experiment to the other. This confusing experimental situation has led, in the last ten years, to an intense phenomenological debate (the E/ι puzzle) on the possibility that one or more of these states are non-q̅q mesons such as glueballs, hybrids or multiquark states [42]. Finally, a recent partial wave analysis of the ι region performed by the MarkIII group (see fig. 12) on the K̅Kπ and ηππ final states from J/ψ radiative decay, has shed a new light on this puzzle [43]. This analysis interprets the ι signal as due to three different resonances

- i) η(1420) with J^PC = 0^{−+} and decay via a_0(980)π. Very likely it has also a substantial ρ^0γ decay mode [14, 15] (see fig. 13a)). This state may be the same as the one observed in p̅p at rest and in π induced reactions. However, it is not observed in γγ collisions nor in central production.
- ii) η(1490) with J^PC = 0^{−−} and a decay via K^*K
- iii) f_1(1440) with J^PC = 1^{++} and a decay via K^∗K

In conclusion, one or more pseudoscalars are present in the 1.4 GeV mass region, and up to now it is not clear whether they are radial excitations, hybrids or glueballs.

7. AXIAL VECTORS

One of the most interesting mesons from the point of view of the possible existence of non-q̅q states is the J^PC = 1^{++} E/f_1(1420) meson.

The best evidence for E/f_1(1420) comes from the Ω − WA76 experiment which studied the reaction pp → p(K̅Kπ)p [46]. The same experiment also studied the centrally produced 4π [47] (fig. 14), ηππ [10] (fig. 3b)) and ρ^0γ [15] (fig. 3b)) final states. While the presence
Figure 12:  a) Partial wave analysis of $J/\psi \rightarrow K\bar{K}\pi$; b) $J^{PC} = 0^{-+}$ intensity from the PWA of $J/\psi \rightarrow \gamma\eta\pi$ (MarkIII).

Figure 13: a) $\rho^0\gamma$ mass spectrum from $J/\psi$ radiative decay (MarkIII); b) $\rho^0\gamma$ mass spectrum from central production ($\Omega$-WA76).
of the axial meson $f_1(1285)$ was observed in all these spectra, the $f_1(1420)$ was found to decay only to $K^*\bar{K}$. The classification of the $E/f_1(1420)$ in the quark model is still unclear, its quantum numbers are sometimes subjected to criticism and its interpretation as a normal hadronic resonance is not without problems. It was considered, until recently, to be the $s\bar{s}$ member of the axial nonet. However, this hypothesis is in contradiction to several experimental results, namely:

- i) It is not produced in $K^-$ induced reactions, where an $s\bar{s}$ state should prominently appear. On the other hand a different axial resonance, the $f_1(1520)$, has been discovered in these reactions \cite{18}, which has the expected properties for being the $s\bar{s}$ member of the axial meson nonet (see fig. 14b).

- ii) The pattern observed in hadronic $J/\psi$ decay ($J/\psi \rightarrow \omega E$ seen, $J/\psi \rightarrow \phi E$ not seen) \cite{19} (see fig. 15a,c) is inconsistent with a mainly $s\bar{s}$ composition of the $E/f_1(1420)$ meson. The same conclusion is obtained from the observed rates for production of this resonance in $\gamma\gamma^*$ collisions (see fig. 15): $\Gamma_E$ is too large for a mainly strange meson \cite{50}.

Figure 14: a) $K\bar{K}\pi$ mass spectrum centrally produced in pp interactions ($\Omega$-WA76); b) $K\bar{K}\pi$ mass spectrum from an incident $K^-$ beam (LASS).

These arguments lead to two possibilities: either the $E/f_1(1420)$ belongs to the axial nonet with a mixing angle far from the ideal one leaving the $f_1(1520)$ as an extra state or, more reasonably, the $E/f_1(1420)$ is an extra resonance which does not fit into the quark model. In the latter case it is interesting to understand what it really is: a hybrid meson (see fig. 16 \cite{51}), a $K^*\bar{K}$ or a multiquark state \cite{50,52}?
Figure 15: Comparison between the $K\bar{K}\pi$ mass spectra from: a) $J/\psi \rightarrow \gamma K\bar{K}\pi$, b) $J/\psi \rightarrow \omega K\bar{K}\pi$, c) $J/\psi \rightarrow \phi K\bar{K}\pi$ (MARKIII); d) $\gamma\gamma \rightarrow K\bar{K}\pi$, e) $\gamma\gamma^* \rightarrow K\bar{K}\pi$ (TPC/2$\gamma$)

Figure 16: Possible decay of a hybrid meson to $K^*\bar{K}$
8. THE SEARCH FOR THE $J^{PC} = 1^{-+}$ EXOTIC STATES

The discovery of an exotic $1^{-+}$ combination, which is impossible to form with quarks only, would give a strong push to gluonium spectroscopy. For this reason great interest was provoked by the claim of the GAMS experiment of having found one of these states in the $\eta\pi^0$ mass distribution from incident $\pi^-$ beams [53]. The $\eta\pi^0$ mass spectrum from this experiment is dominated by a large $a_2(1310)$ resonance. However, a partial wave analysis of the $\eta\pi^0$ mass spectrum revealed the existence, below the large tensor wave, of a smaller but significant spin 1 wave interpreted as the evidence of a $1^{-+}$ resonance ($\rho(1406)$) having a mass of 1406 MeV and $\Gamma = 180$ MeV (fig. 17). The presence of a $1^{-+}$ wave in the 1.4 mass region has been confirmed at KEK [27] in the study of the $\eta\pi^-$ final state (fig. 10c), but with somewhat different parameters. However, there are some problems with the analysis method which may yield ambiguous results showing the need of confirmation in different processes.

Other experiments have investigated the $\eta\pi^0$ spectrum in a search for this exotic resonance. In particular the VES experiment, at IHEP has collected large statistics on the reactions $\pi^-N \rightarrow (\eta\pi^-)N$ and $\pi^-N \rightarrow (\eta'\pi^-)N$ finding no evidence for exotic resonance production in the $\eta\pi^-$ and $\eta'\pi^-$ final states (fig. 11a). The same result has been obtained by the Crystal Barrel experiment at Lear which studied the $\eta\pi^0$ system in the reaction $\bar{p}p \rightarrow \pi^0(\eta\pi^0)$ (fig. 18a) [29].

The exotic isospin zero hybrid ($\omega(1^{-+})$) is expected by several models to be in the 1.3-1.6 GeV mass region [54] and to have an important $a_1(1260)\pi$ decay mode. Fig. 19 shows the $2\pi^+2\pi^-$ mass distribution from $\Omega^-WA76$ experiment in the reaction $pp \rightarrow p(2\pi^+2\pi^-)p$ [17]. Along with $f_1(1285)$ and a broad structure peaking at 1900 MeV, a new resonance has been
9. EXOTIC RESONANCES WHICH DECAY TO VECTOR-VECTOR

The study of associated $\phi\phi$ production in $\pi^-p$ interactions was one of the starting points of gluonium spectroscopy. The large and unexpected $\phi\phi$ cross section in $\pi^-p$ interactions has been interpreted as due to the production of three $J^{PC} = 2^{++}$ glueball states in the 2.0 - 2.5 GeV region \cite{57}. Evidence for resonant structures in the 1.6 and 2.0 GeV regions has been recently reported in the $\omega\omega$ system produced by incident $\pi^-$ beams \cite{58}.

One of the most striking effects found in two photon physics is the large cross section for $\gamma\gamma \to \rho^0\rho^0$ below threshold \cite{59}. The much lower $\rho^+\rho^-$ cross section (fig. 20) rules out a single resonance interpretation. To explain this effect in a resonance interpretation requires the introduction of an exotic $I=2$ state interfering with another $I=0$ state, both states being logical candidates for four-quark resonances. Experimental spin parity analyses of the $\rho\rho$ enhancement are controversial; it may be $0^+$ and/or $2^+$. As regards the $J/\psi$ radiative decays, the $\phi\phi$, $\omega\omega$, $K^*0\bar{K}^*0$ and $\rho\rho$ final states are dominated by $J^P = 0^-$ contributions. These spectra show marked threshold enhancements, whereas the $\rho\rho$ final state shows the presence of still unexplained resonant structures \cite{60} (see fig. 21).
Figure 19: $2\pi^+2\pi^-$ effective mass distribution from $\Omega$-WA76 experiment.

Figure 20: $\rho^0\rho^0$ and $\rho^+\rho^−$ cross sections in $\gamma\gamma$ collisions
10. PROSPECTS FOR A TAU-CHARM FACTORY

The unique identification of a glueball or an hybrid state would certainly considered as a fundamental discovery. However, up to now, the situation is rather ambiguous mostly due to the lack of high statistics and high precision data. Simplified analysis of data coming from low acceptance detectors have created much confusion. In this context a Tau-Charm Factory has a good chance to definitively solve the problem of the existence of gluonic mesons [61]. Several different tools would be available at a Tau-Charm Factory:

- 1) Radiative $J/\psi$ decays;
- 2) Hadronic $J/\psi$ decays;
- 3) $\eta_c$ and $\chi$ decays;
- 4) $\gamma\gamma$ collisions.

There are several advantages in using $J/\psi$ to study light meson spectroscopy. These are the following:

- a) $J/\psi$ has well defined initial quantum numbers and is produced with almost no background in $e^+e^-$. This allows one to perform reliable spin parity analyses with a small number of amplitudes.
- b) At a Tau-Charm Factory it could be possible to easily obtain very large statistics.
- c) Its mass is ideal for exploring masses up to 2.5 GeV. Its decay patterns involve gluons (so that glueballs could be formed) and mixtures of quarks and gluons (for searching...
for hybrids).

- d) By comparing rates for \( J/\psi \rightarrow \gamma + M_1 \) to those for \( J/\psi \rightarrow M_1 + M_2, \eta_c \rightarrow M_1 + M_2, \chi_{c0,1,2} \rightarrow M_1 + M_2 \) one can determine the spin and the quark/gluon content of a given resonance.

The actual number of \( J/\psi \) decays collected up to now by several experiments are summarized in fig. 22 and they do not exceed \( 10^7 \). At a Tau-Charm Factory this number could easily grow to \( 10^9 \) and simultaneously it could be possible to obtain of the order of \( 10^7 \) \( \eta_c \) or \( \chi \) decays through the chains:

\[
J/\psi \rightarrow \gamma \eta_c \\
\psi' \rightarrow \gamma \chi_{c0,1,2}
\]

The radiative \( \psi' \) decays to \( \chi \)'s have quite large branching rations, between 8 and 9 %.

Figure 22: \textit{Number of collected \( J/\psi \) decays from the different experiments (\( \times 10^6 \)).}

Two photon physics is an important laboratory for studying light meson spectroscopy. Glueballs should not be produced but hybrids and four-quark resonances are accessible. Therefore, by comparing results from \( J/\psi \) decays to those coming from photon-photon physics, it is possible to obtain further information on the properties of exotic candidates.

At a Tau-Charm Factory, the presence of an electromagnetic calorimeter at small angles allows the detection of single and double tag events. This is a unique possibility among the existing machines, even if the limited center of mass energy allows the detection of resonances only in the low mass region, up to 2 GeV.

11. CONCLUSIONS

It is now 13 years since the discovery of the glueball candidate \( \iota(1440) \) in radiative \( J/\psi \) decay. Due to a large amount of experiments performed at a large variety of fixed target and collider experiments, this frontier of physics has advanced considerably in the last years. At
present there are some "solid" candidates, but the unambiguous identification of glueballs
or hybrids is still missing.

In all the $J^{PC} = 0^{++}, 0^{-+}, 1^{++}$ and $2^{++}$ sectors, the number of observed states in the 1 –
2 GeV mass region is possibly larger than predicted by the quark model. The extra states –
if their $J^{PC}$ are confirmed – are good candidates for non-qq states, but their nature will not
be elucidated without a concerted search in a large number of production mechanisms. The
validation of any state as glueball is strongly dependent on its observation in the decay of
$J/\psi$’s copiously produced at a $\tau$-charm factory. Very large data sets (for reliable partial wave
analyses) and a detector covering as large a solid angle as possible (to minimize distortions
decay angular distributions due to acceptance) are requisites for observation and accurate
determination of the $J^{PC}$ of all candidate states, and for an unambiguous identification of

The next decade should possibly solve this QCD low energy puzzle by using high quality
and high statistics data. A Tau-Charm factory is probably one of the best places where this
type of research can be performed.

Acknowledgments
We thankfully acknowledge discussions with T. Barnes, D. Bauer, F. Close, A. Falvard,
M. Feindt and R. Landua.

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