GLUEBALL SPECTROSCOPY AND THE ROLE OF
A TAU-CHARM FACTORY

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Abstract

The glueball spectrum is one of the least understood features of the Standard Model. All low-energy approximations of QCD predict bound states of gluons (glueballs), and there is a consensus that the (scalar) ground state should be in the 1–2 GeV mass range. Recent results from the Crystal Barrel experiment at LEAR suggest that a scalar glueball has indeed been discovered at 1500 MeV. A comparison with results from Mark-III and DM2 indicates that it may already have been seen in radiative $J/\psi$ decays, albeit with insufficient statistics. A very high statistics study of $J/\psi$ decays at the Tau-Charm Factory (TCF) is now essential to confirm this result and to find other members of the glueball spectrum.
1 Introduction

There is little doubt that radiative $J/\psi$ decays are the best place to search for glueballs: the two-gluon system gives access to spin-parity states predicted for the lowest lying ($C = +1$) glueballs, and the energy region covers the range of predicted glueball masses. The experiments at SLAC and DCI produced very interesting results, yet the lack of statistics and the limited acceptance of the detectors left many questions concerning the nature of the newly found resonances. In the light of recent results from the Crystal Barrel experiment at LEAR, suggesting the existence of a scalar glueball at 1500 MeV, it is worth while to look again at the published spectra from radiative $J/\psi$ decays. Indeed there is some evidence for $f_0(1500)$ in several final states, albeit with insufficient statistics in most cases. It is therefore argued that a high-statistics and large-acceptance experiment at a Tau-Charm Factory (TCF) is urgently needed to confirm this result and to explore the glueball spectrum.

The article is organized as follows: Section 1 gives a brief overview of the various QCD-based models for low-energy quark–gluon interactions, which are also used to calculate glueball masses. Section 2 puts important results on $J/\psi$ decays from SPEAR, DCI, and BEPC into perspective: the observation of the $E/\epsilon(1440)$, $f_J/\Theta(1700)$, $\xi(2220)$, and the use of flavour filtering as an analysis tool. Section 3 describes the new findings of Crystal Barrel at LEAR. Using a high-acceptance, high-resolution detector for charged and neutral particles, and studying selected final states with very high statistics (> 100 000 events), an excellent glueball candidate, the $f_0(1500)$, has been discovered. Finally, Section 4 outlines the potential of a TCF to unravel the glueball spectrum and describes the measurements needed to finally settle this question experimentally.

This article is dedicated to new developments in glueball spectroscopy. For comprehensive overviews about the results on the study of $J/\psi$ decays or of the search for other exotics, like hybrids, four-quark states, or meson–meson molecules, the reader is referred to recent reviews [1].

1.1 QCD and glueballs

The SU(3)-flavour quark model [2] gives a qualitative understanding of the meson and baryon multiplets, but only the formulation of QCD [3] has enabled theory to calculate the interactions of colour-charged quarks and gluons. The experimental fact that the spectrum of hadrons is dominated by baryons ($qqq$) or mesons ($q\bar{q}$) is taken care of by postulating that only colourless states are observable. However, being a SU(3)-colour gauge theory with self-interacting gauge fields, QCD retains an own spectrum of bound states of gluons even after removing the quarks. These bound states of gluons, called glueballs, are a ‘strict consequence of QCD’ [4]. Yet, in spite of more than 20 years of theoretical effort, it has not been possible to calculate the glueball spectrum from first principles, since perturbative QCD cannot be applied at hadronic mass scales. Therefore, several models have been developed, differing in their assumptions about the degrees of freedom needed to reproduce QCD at low energies most accurately. Further progress now is linked to more detailed experimental information about the glueball spectrum as a guidance. In its absence, it remains unclear if the self-interaction of massless gauge fields at low energies is correctly understood, leaving an essential gap in tests of the Standard Model.

The main purpose of the following brief overview of the various models attempting to calculate glueball properties is to show that in spite of the very different approaches a common prediction has emerged: the ground-state glueball has scalar quantum numbers, and its mass is about $1.5 \pm 0.3$ GeV.

In the bag model, free quarks or gluons are confined to a spherical bag with radius $R \sim 1$ fm, where they interact by the colourmagnetic, Coulomb-like potential
given by the QCD Lagrangian. The constituents are confined by the introduction of a bag surface pressure $B_0$. The earliest calculation of two gluon states in the bag model was done by Jaffe [5]. These calculations gave a mass of 960 MeV for the scalar and tensor ($J^P = 0^+, 2^+$) glueball, 1290 MeV for the $0^−$ and $2^−$ states, and 1590 MeV for the next scalar/tensor doublet. Barnes and Close [6] later refined these calculations and found a scalar glueball at 1.0 ± 0.2 GeV, followed by a tensor glueball at 1.6 GeV. The mass predictions are mainly affected by large uncertainties of $R$ and $B_0$, which are not necessarily the same parameters as for the $q\bar{q}$ meson spectrum. A general feature of most bag model calculations is the level ordering $m(0^{++}) < m(0^{−+}) < m(2^{++}) < m(2^{−+})$ of the glueball mass spectrum.

**Potential models** start from massive ‘constituent’ quarks ($m_u \approx m_d \approx 300$ MeV, $m_s \approx 500$ MeV) and—for the calculation of glueball masses—massive gluons. They interact by a Coulomb-plus-linear potential ($-\alpha_s/r + br$). A fit to the meson mass spectrum fixes the free parameters of the respective model. Predictions in the glueball sector are less certain, since the confinement parameters for glueballs could be different from those of $q\bar{q}$ states. The model of Barnes [7] includes the effects of hyperfine interactions (Fermi–Breit potential), and he finds the level ordering $m(0^{++}) \approx m(0^{−+}) < m(2^{++}) \approx m(2^{−+})$. The degeneracy of two glueballs with the same spin but opposite parity is an interesting consequence of his model. Assuming that the pseudoscalar glueball has a mass $M = 1.44$ GeV, the scalar glueball would have a similar mass, while the tensor glueball would be around 1.65 GeV.

In lattice QCD, Feynman path integrals are evaluated on a discrete space–time lattice, where quarks live on sites and gluons live on links. Using this method, Wilson [8] demonstrated that QCD confines in the strong coupling limit. Glueball masses are calculated by a Monte Carlo simulation of two-point correlation functions between operators with glueball quantum numbers. This method has the significant advantage of allowing first principle calculations based on the QCD Lagrangian. However, in practice it still suffers from systematic uncertainties due to the limitations of present computers: the lattice spacing must be small enough to obtain the correct mass in the continuum limit, i.e. much smaller than the size of the glueball wave function; on the other hand, the total lattice size should be much bigger than the glueball wave function. Recent progress in understanding this systematics has reduced the estimated error of absolute mass predictions to about 100 MeV. However, fermion loops are still not taken into account because of the large computational needs they would introduce (‘valence approximation’). The latest results from the UKQCD collaboration [9] are a scalar glueball mass of 1550±50 MeV and a tensor glueball at 2270±100 MeV, while the GF11-IBM team [10] finds the values 1740±71 MeV (scalar) and 2359±128 MeV (tensor). The tensor and pseudoscalar glueballs are in the same mass range. It is generally believed that mass ratios (e.g. $M_{\text{Tensor}}/M_{\text{scalar}} \sim 1.5$) are more predictable than absolute masses.

The flux tube model [11, 12] is based on the strong coupling flux tube limit of QCD [13]. It describes mesons as a $q\bar{q}$ system connected by a discrete quantum string, which collimates the chromoelectric field strength between two (static) colour charges. The string executes zero-point fluctuations about the $q\bar{q}$ axis. The arising long-range force increases linearly with distance and is spin-independent, in contrast with the short-range colour-electric potential. Using this model, Godfrey and Isgur [14] have performed a very comprehensive set of calculations, and the agreement with the spectrum of well-established $q\bar{q}$ resonances is very good. Their predictions have become a very important guide for distinguishing candidates for ‘exotics’ from the meson ‘background’. Glueballs are formed in the flux tube model by removing the quarks and joining the ends of the flux tubes. As in the other models, uncertainty about the glueball mass scale arises from the lack of knowledge of the parameters for
a string between two gluons. For a certain choice of parameters, the scalar glueball is predicted at 1.52 GeV, while the pseudoscalar and tensor glueball are both at about 2.8 GeV [12].

**QCD Sum Rules** were invented [15] to relate information from low-energy reactions with the asymptotic regime of QCD. Weighted integrals of the colliding $e^+e^-$ beam cross-section $R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \muons)$ are linked to matrix elements of local operators. These local operators are two-point functions associated with currents carrying the same quantum numbers as the resonance to be studied, and they are calculable in terms of short-distance properties of QCD. It was shown that the mass and width of the $\rho, \omega,$ and $\Phi$ are indeed correlated with short-distance parameters of QCD. Encouraged by this success, the sum rules were applied to operators carrying glueball quantum numbers. The scalar glueball is predicted at 1.5 GeV, while the $0^{-+}$ and $2^{++}$ states are both above 2 GeV [16].

### 1.2 Production and decay of glueballs

The production of glueballs is favoured in a ‘gluon-rich’ environment, like radiative $J/\psi$ decays, central hadron collisions, and antiproton–proton annihilations.

Radiative $J/\psi$ decay is the prime channel for glueball searches: after emitting a photon, the $c\bar{c}$ pair is in a $C = +1$ state and decays to hadrons dominantly through two-gluon intermediate states. Thus, any resonance recoiling against a photon is a potential glueball candidate [17]. Of course, ordinary $S$- and $P$-wave mesons are also produced. Some of these branching fractions have been calculated by Köhler et al. [18] using a model based on perturbative QCD. The results are in fair agreement with the data, although $c\bar{c}$ annihilation occurs at $q^2 \approx 10 \text{ GeV}^2$, where the validity of perturbative QCD is doubtful. Farrar [19] used a similar model to calculate glueball production rates, making additional assumptions about the probability that two gluons ‘hadronize’ into a glueball, and finds typical branching ratios of a few $10^{-3}$. Based on lattice calculations, Liang et al. [20] calculated transition matrix elements and derived partial widths of $J/\psi$ radiative decays of about $5 \times 10^{-3}$ for a scalar glueball.

Central proton–proton collisions [21] are favourable to ‘gluon–gluon fusion’, since about half the proton momentum is carried by gluons. The creation of glueballs is assumed to proceed via the collision of two ‘pomerons’, presumed to be colourless multi-gluon states. In antiproton–proton annihilation, gluons in the appropriate momentum range are produced by the annihilation of one or two $q\bar{q}$ pairs [22]. For the latter two reactions, the complicated initial state makes predictions of glueball production rates impossible.

In contrast, $\gamma\gamma$ collisions do not produce glueballs in leading order: since gluons do not carry electric charge, their coupling to photons can only come from $q\bar{q}$ pair creation. This suppression distinguishes glueballs from $q\bar{q}$ mesons with a larger and well-known coupling to $\gamma\gamma$ initial states.

The present status of theory does not allow accurate predictions of absolute decay widths of glueballs. More general principles are however useful to study relative decay widths. A glueball is an SU(3) singlet ($I = 0$) state, consisting of flavourless and electrically neutral gluons, and hence has at first no preferential coupling to any quark flavour. A ‘pure’ glueball with positive C-parity should therefore decay equally into final states like $\pi\pi, \eta\eta, K\bar{K}$, but not into $\eta\eta'$ (no SU(3) singlet). The relative decay strengths of glueballs are given by the SU(3) flavour content of the final state (3 for $\pi\pi$, 4 for $K\bar{K}$, 1 for $\eta\eta$), modified by phase space factors $q^{2L+1}$. Glueballs can also decay into multi-particle final states via intermediate resonances, e.g. into $4\pi$ (via $(\pi\pi)_s(\pi\pi)_s$ or $\rho\rho$), $\Phi\Phi$ or $\omega\omega$. This is different from ordinary $q\bar{q}$ mesons, whose decay pattern is related to their quark content and the SU(3) mixing angle of the respective nonet.
However, this simple picture may not be manifested in nature: $q\bar{q}$ mesons with similar mass and the same quantum numbers will mix with the glueball and let it acquire some of their $(q\bar{q})$ decay characteristics; the coupling to $\eta$ and $\eta'$ states may be enhanced due to a possible admixture of a pseudoscalar glueball to these pseudoscalar mesons; it has also been suggested that confined gluons couple stronger to heavier quark pairs.

An identification of a glueball is therefore closely linked to an understanding of the near-by $q\bar{q}$ nonet with the same quantum numbers. The masses, decay characteristics, and mixing angle of this meson nonet are needed to estimate the mass shift and the change of decay properties of the glueball.

### 1.3 Glueball search strategy

In spite of using very different approximations, all models predict the existence of glueballs in the 1–2 GeV mass range. They also agree that the scalar glueball is the ground state, with a mass around 1.5 GeV. Most models then predict the pseudoscalar and the tensor glueball at about 1.5 times the ground-state mass (2.0–2.5 GeV), with the notable exception of Barnes predicting a degenerate $0^{++}$ and $0^{-+}$ state. However, there are still uncertainties about the systematic error introduced by the quenched approximation in lattice QCD, or by the effect of the QCD vacuum (instantons) on the mass of the scalar glueball. The absolute mass scale of the glueball spectrum should therefore be considered with caution by experimentalists, since there is no known ‘calibration point’ for bound states of gluons, which would fix their specific confinement parameters.

Glueballs are likely to be produced in ‘gluon-rich’ reactions, like radiative $J/\psi$ decay, central hadronic collisions, and proton–antiproton annihilation. The search for glueballs concentrates on finding ‘superfluous’ isoscalar ($I = 0$) mesons with scalar, pseudoscalar, or tensor quantum numbers. Then, all possible decay modes of the glueball candidate must be studied against the background of the near-by $q\bar{q}$ nonet, since it may shift the mass and change the decay properties. Finally, the appearance of the candidate resonance in gluon-rich reactions and its absence in gluonless (e.g. photon–photon collisions) processes is a very important ingredient for its classification.

### 2 $J/\psi$ decays at SPEAR, DCI, and BEPC

Shortly after the discovery of the $J/\psi$ it was pointed out that the radiative decay $J/\psi \rightarrow \gamma X$ (Fig. 1) should have a sizeable branching ratio ($\approx 10\%$), where $X$ is a hadronic system with positive $G$- (and $C$-) parity [23]. Later it was also suggested [17] that the two gluons produced in radiative $J/\psi$ decays should couple to $C = +1$ neutral isoscalar resonances, including the $\eta_c, \eta, \eta'$ as well as glueballs.

The systematic study of $J/\psi$ decays was done by two generations of experiments: at first by Mark-II and Crystal Ball at SLAC, then by Mark-III at SLAC and DM2 at DCI Orsay. A comparison of the features and the performance of the different detectors is given in Table 1.

![Figure 1: Leading order graph for radiative $J/\psi$ decay.](image-url)
Table 1: Comparison of detectors used to study $e^+e^-$ and $\bar{p}p$ annihilation

<table>
<thead>
<tr>
<th>Detector</th>
<th>$B$ (T)</th>
<th>$\Omega_{\text{charged}}$ (% of $4\pi$)$^1$</th>
<th>$\sigma_p/p$ (pin GeV/c)</th>
<th>$\Omega_{\text{neutral}}$ (% of $4\pi$)$^1$</th>
<th>$\sigma_E/E$ ($E$ in GeV)</th>
<th>$\langle \sigma_{\theta,\phi} \rangle$ (mrad)</th>
<th>$E_{\text{thresh}}$ (MeV)</th>
<th>Particle identification</th>
<th>Statistics (10^6 J/ψ decays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Ball</td>
<td>0.0</td>
<td>94 (0)</td>
<td>None</td>
<td>98 (85)</td>
<td>2.6% $E^{-1/4}$</td>
<td>30</td>
<td>20</td>
<td>None</td>
<td>2.2</td>
</tr>
<tr>
<td>Mark-II</td>
<td>0.4</td>
<td>85 (75)</td>
<td>0.5% $p \oplus 1.5%$</td>
<td>64 (64)</td>
<td>12% $E^{-1/2}$</td>
<td>4</td>
<td>400</td>
<td>$dE/dx$, TOF, muons</td>
<td>1.3</td>
</tr>
<tr>
<td>Mark-III</td>
<td>0.4</td>
<td>93 (84)</td>
<td>1.5% $p \oplus 1.5%$</td>
<td>94 (85)</td>
<td>17% $E^{-1/2}$</td>
<td>10</td>
<td>100</td>
<td>$dE/dx$, TOF, muons</td>
<td>5.8</td>
</tr>
<tr>
<td>DM2</td>
<td>0.5</td>
<td>95 (87)</td>
<td>3.5% $p \oplus 1.5%$</td>
<td>82 (70)</td>
<td>19% $E^{-1/2}$</td>
<td>10</td>
<td>110</td>
<td>TOF</td>
<td>8.6</td>
</tr>
<tr>
<td>BES</td>
<td>0.4</td>
<td>95 (70)</td>
<td>1.7% $p \oplus 1.7%$</td>
<td>93 (93)</td>
<td>21% $E^{-1/2}$</td>
<td>8</td>
<td>100</td>
<td>$dE/dx$, TOF, muons</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>EXACT (TCF)</strong></td>
<td>1.2</td>
<td>95 (90)</td>
<td>0.4% $p \oplus 0.4%$</td>
<td>95 (95)</td>
<td>2.0% $E^{-1/4}$</td>
<td>3</td>
<td>10</td>
<td>$dE/dx$, TOF, muons, Cherenkov</td>
<td>100/day</td>
</tr>
<tr>
<td>Crystal Barrel</td>
<td>1.5</td>
<td>95 (70)</td>
<td>5.5% $p \oplus 1.0%$</td>
<td>97 (95)</td>
<td>2.5% $E^{-1/4}$</td>
<td>25</td>
<td>10</td>
<td>$dE/dx$</td>
<td>100 ($p\bar{p}$)</td>
</tr>
</tbody>
</table>

$^1$ First number: Solid angle for detection; second number: solid angle for good momentum (or energy) measurement.
The first results were published in 1980 [24, 25] and showed that the radiative $J/\psi$ decay rate agreed with the prediction from perturbative QCD, confirming the dominance of the $\gamma + gg$ contribution. Crystal Ball published an inclusive $\gamma$ spectrum [25], based on about 0.85 M $J/\psi$ decays (Fig. 2), showing peaks for the $\eta$ and the $\eta'$. The branching fractions ($J/\psi \rightarrow \gamma\eta : 0.86\pm0.08 \times 10^{-3}$; $J/\psi \rightarrow \gamma\eta' : 4.31\pm0.30 \times 10^{-3}$) (1994 values, Ref. [26]) were in reasonable agreement with model calculations [27]. The observation of two additional bumps in the inclusive spectrum, baptized ‘$E/\iota$’ ($\approx 1400–1500$ MeV) and ‘$f_{J/\Theta}'$ ($\approx 1600–1700$ MeV), caused great excitement. Both were prominent and unidentified structures in the prima-facie glueball channel. But were they glueballs?

\[ \begin{align*}
M_X \text{ (GeV)} \\
30 & \quad 2.0 \quad 1.5 \quad 1.0 \\
20 & \quad \Theta \\
10 & \quad \text{E/}\iota \\
0 & \quad \eta' \\
-10 & \quad \eta \\
-20 & \quad \text{CRYSTAL BALL} \\
-30 & \\
0 & \quad E_\gamma \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \quad 1.6 \text{ GeV} \\
\end{align*} \]

Figure 2: Inclusive $\gamma$ spectrum for radiative $J/\psi$ decay (Crystal Ball data).

### 2.1 The $E/\iota$ puzzle

The main decay mode of the peak at 1460 MeV turned out to be $K\bar{K}\pi$, with a branching ratio $BR(\psi \rightarrow \gamma X) \times BR(X \rightarrow K\bar{K}\pi) = (3.6 \pm 1.4) \times 10^{-3}$. The $K\bar{K}\pi$ decay mode is characteristic of pseudoscalar ($J^P = 0^−$) and axial vector ($1^+$) states, and at first the structure was associated with the $f_1(1420)$ meson, an axial vector $I = 0$ resonance observed in hadronic reactions. However, such a large branching fraction for a spin-1 state was surprising, since such states should not be formed by two massless spin-1 gluons (Yang theorem). Chanowitz [28] pointed out that a $0^{−+}$ state at 1420 MeV had been seen in $p\bar{p}$ annihilations at rest [29] and proposed that the signal observed in radiative $J/\psi$ decays might be a superposition of a $0^{−+}$ glueball and a $q\bar{q}$ 1++ state. In 1982, Crystal Ball published a partial wave analysis based on 174 ± 30 events (from 2.2 M $J/\psi$ decays) [30], concluding that the peak was entirely of pseudoscalar nature and baptizing it $\iota(1440)$, since the name ‘$E$’ was now commonly used for the $1^+$ state.
In 1985, Mark-III (SLAC) and DM2 (DCI Orsay) reported new results based on higher statistics (5.8 and 8.6 M $J/\psi$ decays), taken at $e^+e^-$ machines with increased luminosity and with detectors featuring improved charged-particle acceptance and particle identification. The $E/\iota$ signals of Mark-III and DM2 contained about 1000 events each, with $J/\psi \rightarrow \gamma K_0^* K^+\pi^- + c.c.$ being the cleanest channel with the smallest background. The $E/\iota \rightarrow K_s K\pi$ mass distribution showed a clear asymmetry [Fig. 3(a)] and could not be fit any longer by a single Breit–Wigner. The final Mark-III results on the $E/\iota$, based on the analysis of the final states $J/\psi \rightarrow \gamma K\bar{K}\pi$ [31] and $J/\psi \rightarrow \gamma \eta\pi\pi$ [32] concluded:

1) the $E/\iota$ structure is composed of three resonances (widths are given within their 1$\sigma$ limits): the $\eta(1416)(\Gamma = 22–93$ MeV) with dominant $a_0(980)\pi$ decay, the $\eta(1490)(\Gamma = 42–158$ MeV) with dominant $K^*\bar{K}$ decay, and the $f_1(1440)$ ($\Gamma = 48–98$ MeV) with dominant $K^*\bar{K}$ decay;

2) a pseudoscalar resonance $\eta(1400)(\Gamma = 34–60$ MeV), decaying into $\eta\pi\pi$ mainly via $a_0(980)\pi$, compatible with the $\eta(1416)$ in the $K\bar{K}\pi$ channel.

A similar analysis by DM2 [33] agreed on the presence of pseudoscalar and axial vector contributions, but did not find the same masses and decay modes. This may be due to the limited statistics and the non-uniform acceptance of the two detectors which did not allow a unique decomposition of the spin-parity contributions.

A very useful new technique called ‘flavour filtering’ was introduced by the two experiments. It aims at identifying the valence quark content of a resonance by studying its production in conjunction with ideally mixed $I = 0$ mesons (i.e. pure $u\bar{u} + d\bar{d}$ or $s\bar{s}$ states, like $\omega$ and $\Phi$). Since hadronic $J/\psi$ decays proceed dominantly via 3-gluon annihilation with subsequent production of two $q\bar{q}$ pairs (Fig. 4), a meson recoiling against an $\omega$ contains mainly $(u,d)$ quarks, while a meson recoiling against a $\Phi$ must be dominantly $s\bar{s}$.

This technique was used to obtain additional information about the $E/\iota$. A structure around 1420 MeV (consistent with the $1^{++}$ component found in the partial wave analysis) is seen through the ‘$\omega$ filter’, and should therefore contain mainly light quarks [Fig. 3(b)]. On the other hand, no $E/\iota$ signal is visible recoiling against the $\Phi$ [Fig. 3(c)].

At present there is no consistent interpretation of these observations. None of the three resonances has an obvious place in a $q\bar{q}$ nonet. It is interesting to note that the high-mass tail of the $E/\iota$ structure (above 1500 MeV) is accounted for neither in the $\Phi$ nor in the $\omega$ recoil spectrum. Assuming that a glueball would appear in radiative decays, but not recoil against $q\bar{q}$ mesons, then the $\eta(1490)$ would be the best candidate for a pseudoscalar glueball.

The $\eta(1400)$ decays via $a_0(980)\pi$ and is also observed in $p\bar{p}$ annihilation [34] and in $\pi^- p$ reactions [35]. If it is the $\eta(1400)$ observed in the $\omega$ recoil spectrum, then it could be a radially excited pseudoscalar $q\bar{q}$ state—but why so prominent in radiative $J/\psi$ decays when there are so few other signs of radial excitations? The absence of the $f_1(1420)$ in the $\omega$ or $\Phi$ recoil spectrum might then be due to its possible nature as a $K^*\bar{K}$ molecule.

The $f_1(1420)$ is also observed in hadroproduction and in tagged two-photon events [36]. It does not fit well into the axial vector nonet, where the $f_1(1530)$ is a better candidate for the $I = 0$ $s\bar{s}$ state. If the $f_1(1420)$ is the resonance observed recoiling against the $\omega$ (hinting at light valence quarks), then why does it decay so strongly via $K^*\bar{K}$? In this case, the $\eta(1400)$ would have no counterpart in the $q\bar{q}$ filtered spectrum and could be a glueball. This would fit with its appearance in radiative $J/\psi$ decays and $p\bar{p}$ annihilation and its absence in $\gamma\gamma$ collisions. However, its mass would be hard to reconcile with most of the present model calculations.
Figure 3: (a) Radiative decay $J/\psi \rightarrow \gamma K\bar{K}\pi$ (Mark-III). The $E/\psi \rightarrow K\bar{K}\pi$ mass resonance shape is visibly asymmetric and cannot be fit by a single Breit–Wigner shape. (b) Hadronic decay $J/\psi \rightarrow \omega K\bar{K}\pi$ (Mark-III). (c) Hadronic decay $J/\psi \rightarrow \Phi K\bar{K}\pi$ (Mark-III).
2.2 The $f_J(1710)/\Theta$ puzzle

A second unusual resonance baptized $\Theta(1640)$ ($\Gamma = 150–320$ MeV) was discovered in $J/\psi \rightarrow \gamma\eta\eta$ by Crystal Ball [37]. Based on $2.2 \times 10^6 J/\psi$ decays, $39 \pm 11$ events were found, corresponding to a branching ratio $BR(\psi \rightarrow \gamma\Theta) \times BR(\Theta \rightarrow \eta\eta) = (0.49 \pm 0.17) \times 10^{-3}$. Spin 2 was preferred over spin 0, although the low statistics called for attention. Later, Mark-III and DM2 also observed $\psi \rightarrow \gamma\Theta, \Theta \rightarrow K\bar{K}$. The signal in the $K^+K^-$ mass plot [Fig. 5(a)] was clear (400 events), but now appeared at 1720 MeV. It partially overlapped with the $f_2(1525)$ observed in its (dominant) $K\bar{K}$ decay mode. While the first analysis of Mark-III confirmed the initial $2^{++}$ assignment, a more detailed analysis [38] found a dominant spin-0 contribution at 1690 MeV, with only a small spin-2 component at 1850 MeV. The initial spin-2 assignment was explained by $f_2(1525)$ contamination. However, a resonance with similar parameters is also observed in $p-p$ central collisions [39], with clear assignment $J^P = 2^+$. Using the $\omega/\Phi$ flavour filter, there is a resonance at 1700 MeV in $J/\psi \rightarrow \omega K\bar{K}$, indicating the presence of a $I = 0(u\bar{u}+d\bar{d})$ resonance [Fig. 5(b)]. Recolling against the $\Phi$ [Fig. 5(c)], a strong $f_2(1525)$ signal is visible as expected from its dominant $s\bar{s}$ content. A shoulder extends over the 1700 MeV region, pointing towards some $s\bar{s}$ admixture in the $(q\bar{q}?)$ state at 1700 MeV. The main decay modes of the $f_J(1710)$ (as it is currently called by the PDG) are $K\bar{K}$ and $\eta\eta$, speaking in favour of a preferred coupling to strange quarks. Other decay modes have not been observed directly.

If the $f_J(1710)$ has spin 2, there are too many isoscalars in the tensor nonet, which is otherwise well understood. This is the strongest argument in favour of a glueball interpretation, since the radial excitation of the isoscalar $s\bar{s}$ tensor meson is expected above 2000 MeV. In addition, no corresponding signal is observed in $\gamma\gamma$ collisions, which also speaks in favour of its non-$q\bar{q}$ nature [40]. If the $f_J(1710)$ is a scalar particle, it could be the “true” $I = 0(s\bar{s})$ member of the scalar nonet. What would then be peculiar is the strong appearance in radiative $J/\psi$ decays, and its absence in $\gamma\gamma$ collisions.

2.3 Other unexplained structures

Many more significant structures are visible in the published spectra from Mark-III and DM2, and most of them are also not properly understood. With a view of the recent results from Crystal Barrel it appears useful to list some of these.

$X(1500)$. In $J/\psi \rightarrow \gamma\pi^+\pi^-$ and $\gamma\pi^0\pi^0$, all experiments observe an enhancement on the high mass side of the $f_2(1270)$, sometimes as a shoulder, sometimes as a separate peak [Fig. 6(a)], with branching ratios $0.4–0.8 \times 10^{-4}$ [41]. However, the number of events in this region is too small to conclude the existence of a resonance, or to determine its spin-parity.
Figure 5: (a) Radiative decay $J/\psi \rightarrow \gamma K^+K^-$ (Mark-III). The $f_2(1525)$ is observed in its dominant $K\bar{K}$ decay mode, overlapping partially with the $\Theta(1700)$. (b) Hadronic decay $J/\psi \rightarrow \omega K^+K^-$ (Mark-III). (c) Hadronic decay $J/\psi \rightarrow \Phi K^+K^-$ (Mark-III).
Figure 6: (a) Radiative decay $J/\psi \to \gamma \pi^+\pi^-$. Note the little peak at the high-mass side of the $f_2(1270)$. (b) Radiative decay $J/\psi \to \gamma 4\pi$ (DM2). The $X(1500)$ has a width of 120 MeV, and—assuming decay via two ($\pi\pi$) resonance $[J/\psi \to \gamma X, X \to \sigma(700)\sigma(700)]$—can be fit with spin-parity $0^+$. (c) Radiative decay $J/\psi \to \gamma \eta\eta$. The broad structure between 1450 and 1800 MeV is most likely composed of two resonances, and the more massive one is usually associated with the $f_{J/\Theta}(1710)$. 
In \( J/\psi \to \gamma 4\pi \) [Fig. 6(b)] both Mark-III [42] and DM2 [43] find three prominent and unexplained peaks at 1500, 1800, and 2100 MeV. The \( X(1500) \) state has a width of about 120 MeV, and a product branching ratio \( B(J/\psi \to \gamma X(1500))B(X(1500) \to 4\pi) = (1.83 \pm 0.3) \times 10^{-3} \). DM2 published partial wave analyses, based on the assumption of \( \rho \rho \) dominance. Then, all three resonances are best fit with spin-parity 0\(^-\).

However, by dropping this assumption and including decay via two \((\pi\pi)_s\) resonances (the \( \sigma(700) \) enhancement of the \( \pi\pi \) scattering amplitude) it was shown that these peaks are best fit as scalar resonances [44].

In \( J/\psi \to \gamma \eta \eta \) [Fig. 6(c)], the broad structure between 1450 and 1800 MeV is most likely composed of two resonances, with the higher mass state usually associated to the \( f_J/\Theta(1710) \). The peak around 1500 MeV has sometimes been interpreted as the \( f_2(1525) \to \eta \eta \), but the spin-2 assignment could not be verified by a partial wave analysis because of a lack of statistics. Since the \( \eta \eta \) decay mode of the \( f_2(1525) \) has never been observed directly, this assignment needs confirmation, and it is possible that the \( \eta \eta \) enhancement is due to another resonance at \( M \sim 1500 \) MeV.

\( \xi(2230) \). In \( J/\psi \to K\bar{K} \) and \( \gamma K \), Mark-III [45] claimed the observation of a narrow resonance at 2230 MeV, with a width smaller than 45 MeV and a branching fraction of about \( 10^{-4} \). This \( \xi(2230) \) state was not confirmed by DM2 (upper limit \( 2 \times 10^{-5} \)), who observed instead a rather broad structure at 2200 MeV (\( \gamma \sim 200 \) MeV).

Recently, on the basis of 8.6 M \( J/\psi \) decays, BES has reported [46] an independent observation of the \( \xi(2230) \) in \( K\bar{K} \) and \( \eta \eta \) decays, at a lower mass (2201 \pm 6 MeV), a width 27 \pm 11 MeV, and with a branching ratio compatible with the DM2 upper limit. The spin-parity analysis is in progress, but with less than 50 events per final state. Indications of the \( \xi(2230) \) have also been seen in \( \pi^- p \) and \( K^- p \) induced reactions. It is now listed as a spin-4 resonance in the Particle Data Booklet, but with the remark that the spin assignment needs confirmation.

### 2.4 An intermediate summary

It has become clear that the current statistics of about 25 M \( J/\psi \) decays is far too small. One or more glueballs may have been observed, but the situation is more complicated than expected. The two main structures seen in radiative decays \( (E/\iota, \Theta/f_J) \) are probably composite objects with branching ratios at the \( 10^{-3} \) level, and their interpretation is controversial. Many more significant peaks of unknown origin are observed in the 1.5–2.3 GeV region, and only few have been analysed, again mostly because of a lack of statistics.

The Tau-Charm Factory together with an appropriate detector would be the ideal instrument to accumulate sufficiently high statistics data. Before describing the measurements which could be done at the TCF, some recent results from Crystal Barrel will demonstrate the benefits of a large-acceptance and high-resolution detector taking high-statistics data. These results suggest that a scalar glueball exists at 1500 MeV, which was probably also seen in radiative \( J/\psi \) decays.

### 3 Recent results in glueball spectroscopy

#### 3.1 Crystal Barrel at LEAR

The aim of the Crystal Barrel experiment is a comprehensive and high-statistics study of \( pp \) annihilation at rest and in flight up to 2 GeV/c. This reaction is known to produce most of the known mesons, and it is also believed to be a copious source of gluons from the annihilation of one or more \( q\bar{q} \) pairs. It is therefore a good place to search for glueballs, although the initial multi-gluon states have less well-defined space–time properties than e.g. radiative \( J/\psi \) decays. Glueballs are searched for in reactions like \( \bar{p} \to \pi^0 X \), and \( X \to \pi^0\pi^0, \eta\eta, \eta f, K_s K_s \), where \( X \) must have positive parity and even spin \((0^+, 2^+, ...)\), which are the quantum numbers of the scalar or tensor

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The Crystal Barrel detector [47] is a combination of magnetic spectrometer and CsI crystal calorimeter, with high acceptance for charged and neutral particles, an excellent photon energy resolution (2.5% at 1 GeV), and low photon energy threshold (~10 MeV) [see Table 1]. LEAR provides an excellent antiproton beam, allowing the accumulation of very high statistics and the use of selective triggers. Previous studies of $\bar{p}p$ annihilation were mainly done in bubble chambers, and were seriously limited by statistics, the lacking neutral detection and the absence of final-state triggers. The use of a ‘complete’ detector gives access to all final states of $\bar{p}p$ annihilation, in particular to all-neutral final states. Crystal Barrel has already recorded more than 100 million events, representing a 100- to 1000-fold increase in statistics compared to bubble chambers.

The main emphasis of the data analysis has so far been on all-neutral final states, yielding large data samples in the respective Dalitz plots: $\bar{p}p \rightarrow 3\pi^0$ (712 000 events) [Fig. 7(a)], $\pi^0\pi^0\eta$ (374 000 events) [Fig. 7(b)], $\pi^0\eta\eta$ (31 000 events) [Fig. 7(c)], $\pi^0\eta\eta'$ (977 events), and $5\pi^0$ (300 000 events). The $3\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $\pi^0\eta\eta'$ data were first analysed separately [48]–[51] using Zemach spin-parity functions and the K-matrix formalism, which guarantees conservation of two-body unitarity. At present, the $3\pi^0$, $\pi^0\pi^0\eta$, and $\pi^0\eta\eta'$ final states are being submitted to a coupled-channel analysis [52].

Three new scalar resonances have been found: two $I = 0$ scalar resonances, $f_0(1370)$ and $f_0(1500)$, and an $I = 1$ scalar resonance, $a_0(1450)$. The $f_0(1500)$ can be seen clearly as a flat band (hence spin 0) in the $3\pi^0$ Dalitz plot at $M^2 = 2.2$ GeV$^2$, with a width of 120 MeV. The $f_0(1370)$ is a broad structure needed to fit the $3\pi^0$ Dalitz plot. It is also observed in the final state $\pi^0\eta\eta$ (at $M_{\eta\eta}^2 \sim 1.9$ GeV$^2$), and in 5π final states (decaying via $\rho\rho$ and $\sigma\sigma$). The name ‘σ’ is used here as an abbreviation for the broad peak in the $I = 0$ ππ s-wave scattering amplitude around 700 MeV. In the final-state $\eta\pi\pi$, a new scalar $I = 1$ resonance $a_0(1450)$ with $\Gamma = 270$ MeV was found.

The well-known problems of the scalar nonet [53] are mostly due to the $a_0(980)$ and $f_0(975)$ - which may be $K\bar{K}$ molecules rather than $q\bar{q}$ states [54]. Replacing them by the $a_0(1450)$ and $f_0(1370)$, one obtains an almost ideally mixed scalar meson nonet consisting of $f_0(1370)$ ($u\bar{u} + d\bar{d}$, $I = 0$), $a_0(1450)$ ($I = 1$), and $K_0^*(1430)$ ($I = 1/2$). The ninth, missing member, the $f_0(s\bar{s}, I = 0)$, may have been observed in the LASS experiment at $M = 1520$ MeV, but needs confirmation. The $f_{J}(1710)/\Theta$ is another possible candidate.

This leaves the isoscalar $f_0(1500)$ as the ‘tenth member’ of an already filled nonet. It cannot be the missing scalar meson $f_0(s\bar{s}, I = 0)$, because it couples too weakly to $K\bar{K}$. The $f_0(1500)$ is observed in five different decay modes, with peculiar branching ratios: $f_0(1500) \rightarrow \pi\pi : \eta\eta : \eta\eta' : K\bar{K} : 4\pi = 3 : (0.70 \pm 0.25) : (1.00 \pm 0.46) : < 0.36 : > 2.5$. The $K\bar{K}$ upper limit has been derived from published bubble chamber data. This decay pattern is not compatible with the interpretation of the $f_0(1500)$ as a scalar $q\bar{q}$ state [55]. In addition, the width of the $f_0(1500)$ is much smaller than expected from the widths of the $a_0(1450)$ and $K_0^*(1430)$. The observed decay branching ratios can, however, be accommodated if the $f_0(1500)$ is a glueball, mixed with the near-by isoscalar ($u\bar{u} + d\bar{d}$) and $s\bar{s}$ states of the scalar nonet. The decay ratios of the $f_0(1500) \rightarrow \eta\eta'/\eta\eta (1.4 \pm 0.9)$ agree within the measurement errors with the decay of the $G(1590) \rightarrow \eta\eta'/\eta\eta (2.7 \pm 0.8)$, which has been observed in central production by the GAMS experiment, and may be the same resonance.

It is now of utmost importance to firmly establish the branching ratios of the decay $f_0(1500) \rightarrow K\bar{K}$ and to search for the scalar $I = 0$ ($s\bar{s}$) partner, expected in the 1500–1800 MeV mass range. For that purpose the experiment has installed a microstrip vertex detector to trigger on $K_s \rightarrow \pi^+\pi^-$, which will be used in future data taking.
Figure 7: (a) Crystal Barrel Dalitz plot $\bar{p}p \rightarrow 3\pi^0$ (712 000 events). (b) $\bar{p}p \rightarrow \pi^0\pi^0\eta$ (374 000 events). (c) $\bar{p}p \rightarrow \pi^0\eta\eta$ (31 000 events).
3.2 New look at old data

If the $f_0(1500)$ is the scalar glueball, why was it not seen in radiative $J/\psi$ decays? According to Crystal Barrel, there should be an $f_0(1500)$ signal in $J/\psi \rightarrow \gamma 2\pi$, $\gamma 4\pi$, and $\gamma \eta\eta$. With hindsight, there is indeed a suspicious coincidence of structures around 1500 MeV (Fig. 6) in these final states. The most prominent peak is found in $J/\psi \rightarrow \gamma 4\pi$ at $M \sim 1500$ MeV, width $\Gamma = 100–150$ MeV, and $BR \approx 2 \times 10^{-3}$. As pointed out in Section 2.3, this state is indeed well fit by a $0^+$ resonance [44], in contrast to the original analysis reporting a $0^-$ state [43].

In $J/\psi \rightarrow \gamma \pi\pi$, both the $\pi^0\pi^0$ and $p^+p^-$ mass spectra show a shoulder at the high mass side of the $f_2(1270)$, a fact remarked upon by Mark-III and DM2. For example, DM2 even tried a fit and found the parameters $M = 1507 \pm 8$ MeV, $\Gamma = 86 \pm 8$ MeV. The peak was sometimes associated with $f_2(1525) \rightarrow \pi\pi$, but since this decay mode is very weak, it cannot account for the observed intensity. Finally, in $J/\psi \rightarrow \gamma\eta\eta$ (DM2), the entries in the 1500–1600 MeV region were usually attributed to $f_2(1525) \rightarrow \eta\eta$, but the statistics was insufficient to corroborate the spin-2 assignment. It may well be that the $f_0(1500) \rightarrow \eta\eta$ is seen here.

The $f_0(1500)$ may also have been already observed in central production. A recent publication from WA91 shows that the narrow scalar resonance observed at 1450 MeV [56] can also be fit by the (destructive) interference of the $f_0(1370) - f_0(1500)$ system with the parameters found by Crystal Barrel [57].

In summary, there are strong indications that the $f_0(1500)$ has been observed in all gluon-rich production mechanisms ($\bar{p}p$ annihilation, radiative $J/\psi$ decay, central production). It is an additional isoscalar member of the scalar nonet. It decays mainly to $4\pi$ and $2\pi$, weakly to $\eta\eta$ and $\eta\eta'$, and it has a suppressed $K\bar{K}$ mode. These decay characteristics are not compatible with an ordinary SU(3) $q\bar{q}$ meson. It has not been observed in $\gamma\gamma$ collisions. These observations make the $f_0(1500)$ the best glueball candidate to date.

4 Glueball spectroscopy at the TCF

The construction of a Tau-Charm Factory is now needed more than ever. It is essential to study the production and decay of the $f_0(1500)$ in a clean environment which can only be provided by radiative charmonium decays, but not by $\bar{p}p$ annihilation or central production. The pseudoscalar and tensor glueball are still waiting to be discovered. Since the LEAR facility at CERN will close for budgetary reasons in 1996, an essential part of this work will not be completed. The lesson learnt from Crystal Barrel is that an unambiguous discovery of new structures needs a statistics in the Dalitz plot of about 100 000 events or more. Radiative $J/\psi$ decays have typical branching ratios of $10^{-3} - 10^{-4}$, so that about $10^9$ recorded $J/\psi$ decays are required, which could be obtained within 10 days at the TCF. With the excellent acceptance of the EXACT detector (see Table 1, Ref. [58]), different spin-parity hypotheses can be well separated, and the very good particle identification will suppress background from other final states. A CsI calorimeter will give access to all-neutral final states (like $\gamma\pi^0\pi^0$, $\eta\eta$, $\eta\eta'$, $K_0K_0$, $K^+K^-$, $4\pi^0$, $\omega\omega$, $\Phi\Phi$) would be the starting point. Since any new state found in radiative $J/\psi$ decays may still be an ordinary $q\bar{q}$ meson, it is mandatory to exploit the technique of flavour filtering to understand the $q\bar{q}$ valence quark content. At a TCF, the high luminosity
will also give a greatly enhanced rate for $\gamma \gamma$ collisions: these are ‘anti-glueball filters’, since the production of glueballs is suppressed with respect to $q\bar{q}$ mesons. In addition, the absolute $\gamma \gamma$ width of a $q\bar{q}$ state is reasonably well calculable and can be used to confirm or to confute the $q\bar{q}$ nature of a newly found state. The presence of an electromagnetic calorimeter at small angles will allow the detection of single- and double-tag events, which is a unique possibility among the existing machines.

A new opportunity at the TCF will be the study of $\chi$ decays. The $\psi'(3685)$ decays with $(25.8 \pm 1.4)\%$ probability into $\chi_{c0}$, $\chi_{c1}$, or $\chi_{c2}$. After a period of 100 days at the $\psi'$ energy, the statistics on $\chi$ decays is comparable to the present statistics on $J/\psi$ decays. The specific advantage of such a study is that the three $\chi$ states only differ in angular momentum, while the $c\bar{c}$ content and the radial wave function remain invariant. The dependence of the production of specific mesons on the initial angular momentum will shed light on the spin-parity of the final state. Also, a complementary study of radiative $\chi$ decays would be very helpful in identifying glueballs and other exotics with quantum numbers not accessible to $q\bar{q}$ states.

In conclusion, we may have entered the era of glueball spectroscopy, giving a mechanism for studying the self-interaction of gauge bosons in the non-perturbative regime of QCD. Although the $f_0(1500)$ mass indeed agrees very well with recent predictions of lattice QCD, it is not yet clear if the absolute mass scale of lattice QCD is correct. For example, various systematic errors could contribute to mass shifts compensating each other to some degree. Another ‘calibration’ point from the tensor and/or pseudoscalar glueball would therefore be important to map the lattice results unambiguously onto the real world. If successful, this would boost the confidence in the predictive power of lattice QCD, which is often used in the calculation of hadronic matrix elements needed to test other Standard Model predictions.

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