LAL 87-40
Sept. 1987

Laboratoire de l'Accélérateur Linéaire

EXPERIMENTAL SEARCH FOR GLUONIC MESONS

François COUCHOT

Talk given at the 2nd International School of Physics with Low Energy Antiprotons "Spectroscopy of Light and Heavy Quarks" Erice-Trapani, Sicily, May 24-31, 1987

U.E.R
de
l'Université Paris-Sud

Institut National
de Physique Nucléaire
et
de Physique des Particules

Bâtiment 200 - 91405 ORSAY Cedex

LAL 87-40
Sept. 1987

EXPERIMENTAL SEARCH FOR GLUONIC MESONS

F. Couchot

Laboratoire de l'Accélérateur Linéaire

Orsay, France

Introduction

The gluonic mesons were first mentionned in 1972, at the very beginning of Quantum Chromo Dynamics (Q.C.D.), when H. Fritzsch and M. Gell-mann[1] suggested that "meson states would appear that act as if they were made of gluons rather than $q\bar{q}$ pairs". These states would build "a sequence of extra SU(3) singlet meson states" ; flavour SU(3) nonets could no longer describe all the low mass mesons.

Glue, gluonia or glueballs are the present names of gluonic mesons, and they would be the only example of matter built only with bosons. Their prediction initiated many experimental and theoretical investigations, and the first candidates have been discovered in the beginning of the eighties [2].

The present experimental situation is very rich and rather complex[3], so this paper is not a full revue of the state of the art, but an approach of several methods that have been used to reach the world of glue.

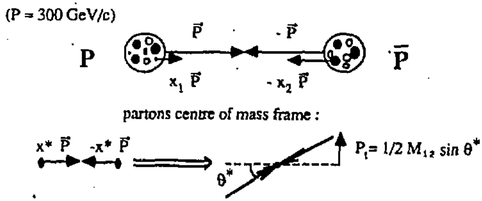
I. THEORETICAL APPROACH

In the Lagrangian of Q.C.D., the self-energy term of the gluon field generates terms of orders 3 and 4 in the field, which manifest themselves as pointlike couplings of 3 and 4 gluons. These couplings lead to a non trivial gluon theory, whereas an electronless theory of electromagnetism would have only free photons.

Up to 1987, we had no direct experimental evidence for the existence of the three gluons vertex. UA1[4] and UA2[5] experiments on the $p\bar{p}$ collider at CERN have given one through the study of the production of two low invariant mass jets. If that result is not a proof of the existence of gluons bound states, it strenghtens the motivation for their search.

I. Evidence for the 3 gluons vertex in the $p\bar{p}$ *minijets*

The events $p+\bar{p} \rightarrow$ jet+jet come from the diffusion of a constituent of the proton on a constituent of the anti-proton. These constituents are the valence and sea quarks and the gluons, each type carrying about half of the total momentum of the proton. The distributions of their momenta are the proton structure fonctions.



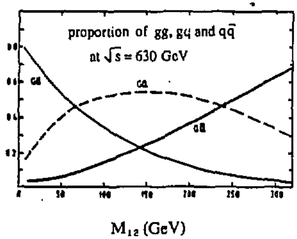


Fig. 1.

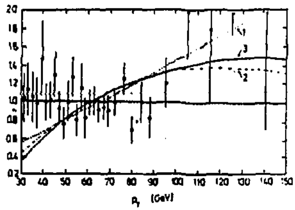


Fig. 2.

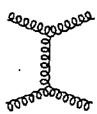
With the above defined kinematical variables, neglecting the masses with respect to the momenta, the invariant mass M_{12} of the two jets is equal to $2\,P\,\sqrt{x_1 x_2} = 2\,P\,x^*$. That gives, for example, at $M_{12} = 25$ GeV, $x^* \approx 25/600 \approx 0.04$.

The gluons dominate the structure function of the proton at low x ($x < 0.1$). Then, most of the events at low M_{12} mass are of the type $g+g \rightarrow$ jet+jet, as shown on figure 1[4].

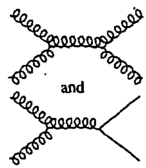
Figure 2[5] shows the measured cross section for $p+\bar{p} \rightarrow$ jet+jet , as a function of P_t, normalized to the Q.C.D. prediction. Below 40 GeV, it is dominated by the process $g+g \rightarrow$ jet+jet. It is well described by Q.C.D., whereas several models without gluon interactions lead to curves 1 to 3, in disagreement with the data.

The description of the process $g+g \rightarrow$jet+jet in QCD is given by the following diagrams :

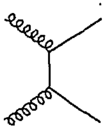
diffusion :



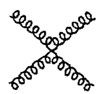
annihilation :



quark exchange :



four gluons interaction :



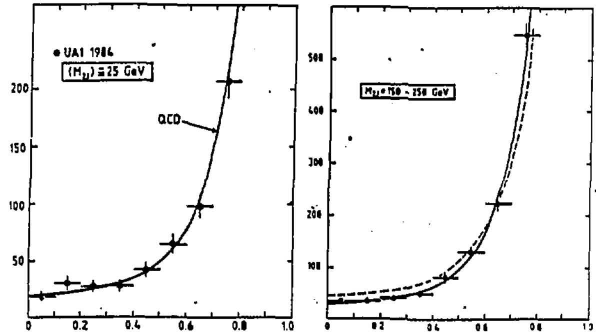


Fig. 3.

Each of these diagrams has its own angular dependence. *The diffusion term is proportional to* $1/(1-\cos\theta^*)^2$ and dominates at $\cos\theta^* > .5$. This angular dependence is characteristic of the exchange of a vector through the t channel. Small angle Bhabha scattering, Rutherford scattering which are dominated by one photon exchange, and the process $q+\bar{q}\rightarrow$jet+jet at high values of $\cos\theta^*$, also dominated by the exchange of a gluon, have the same behaviour.

UA1 has measured the angular distribution of jet pairs at values of $\cos\theta^*$ high enough to show the presence of the diffusion term. Figure 3[4] shows the $\cos\theta^*$ dependence of the jets for two sets of jet-jet invariant masses : the lower one selects $g+g\rightarrow$jet+jet, and the higher one selects $q+\bar{q}\rightarrow$jet+jet events.

These distributions are well fitted with the QCD diffusion term, which is a strong argu*ment for the presence of the exchange of a gluon in the gluon-gluon diffusion, due to the* three gluons coupling.

2. *Origin of the gluon couplings*

In the Lagrangians of Q.E.D., Q.C.D. and of the electroweak theory, the kinetic energy of the gauge field A_μ is given by

$$\mathcal{L}_g = -1/4 \, \mathrm{Tr}\, F^2_{\mu\nu} \text{ with } F_{\mu\nu} = \delta_\mu A_\nu - \delta_\nu A_\mu + g[A_\mu, A_\nu] \; ^{6)}.$$

In Q.E.D., the gauge group is U(1), A_μ is the quadrivector of the electro-magnetic potential, and $[A_\mu,A_\nu]=0$. $\mathcal{L}_g = 1/2\,(E^2+B^2)$ is the free photon energy.

In the two other cases, the gauge group is non abelian, and the A_μ are tensor objects. The commutator of the fields is proportional to their product and introduces couplings between the gauge fields.

In the electroweak theory, the gauge group is $SU(2)\times U(1)$ and there are 4 gauge fields to describe the $W^\pm$, the Z^0 and the photon.

For Q.C.D., the gauge group is color SU(3) and $A_\mu = \sum_{i=1}^{8} \lambda_i A_\mu^i$, where the λ_i are 3×3 matrices generators of SU(3), and the A_μ^i are 8 quadri-potentials that describe the 8 gluon fields. The gluons energy term is given by

$$\mathcal{L}_g = -1/4 \sum_{i=1}^{8} \mathrm{Tr}\,(\delta_\mu A_\nu^i - \delta_\nu A_\mu^i + g\, f^i_{jk}\, A^j_\mu\, A^k_\nu)^2 ,$$ where the f^i_{jk} are the SU(3) structure constants. In the development of $\mathcal{L}_g$, the terms $g\, f^i_{jk}\, A^j_\mu\, A^k_\nu\, \delta^\mu A^{\nu i}$ are the source of the 3 gluon coupling and the terms $g^2\, f^i_{jk} A^j_\mu\, A^k_\nu\, f^i_{lm} A^{\mu l} A^{\nu m}$ the source of the 4 gluon coupling.

3. The glueball hypothesis

These couplings imply that the gluon physics is not a free field one. This is not sufficient to prove that gluon bound states exist. Actually, the $Z^\circ W^+ W^-$ vertex, in the electroweak theory, does not lead to the existence of bound states of intermediate bosons. The size of such states should have the order of magnitude of the weak interaction range, which is given by the Z° mass ($d \approx \hbar c / M_{Z^0} \approx 10^{-18}$m). On the other side, the Heisenberg uncertainty principle would force each constituent to have a momentum of the order of $p \approx M_{Z^0}/c$, which means a kinetic energy of the order of 100 GeV.Then, the existence of bound states needs binding energies greater than 100 GeV, out of the reach of the weak interactions.

The same argument is true for the other types of interactions. It shows that the existence of atoms is partly due to the infinite range of the electromagnetic interactions (i.e. zero mass of the photon). In the case of low mass states bound by strong interactions, the forces have a large range and the binding energies are of the same order of magnitude as the effective masses of the constituents. These two features favour the existence of bound states of gluons.

To go further and predict masses, widths, quantum numbers, decays and production processes for the gluonic states, five models have been used : perturbative Q.C.D.(1), potential models (2), bag models (3), Q.C.D. sum rules (4) and lattice gauge calculations (5). The last four models are different ways of taking into account the non perturbative aspect of strong interactions. They all predict the existence of gluonic mesons in the same mass region as ordinary light quark mesons (.5 to 2. GeV/c^2)[7], with J^{PC} equal to 0^{++}, 0^{-+} and 2^{++}.

4. Glueball properties

The first consequence of the existence of glue, as announced in the introduction, is the fact that flavour SU(3) cannot describe the whole set of mesons. Unfortunately, this does not imply the existence of pure glue states, because the additionnal degree of freedom offered by glue is not orthogonal to others, all these states being expected in the same mass region. Then, the physical states are likely to be mixings of glue and $q\bar{q}$ states. Therefore, even if the glue has very peculiar properties, it is possible that the observed mesons don't exhibit them.

So, the search for glue is strongly related to the knowledge of ordinary mesons.

Quantum numbers

The glueball candidates must have no electric charge and a zero isospin.

Some of the excited states of the 2 and 3 gluons systems have exotic J^{PC}, unaccessible to the $q\bar{q}$ systems[8]. 1^{-+}, 0^{--} 0^{+-} and 2^{+-} are some of these exotic J^{PC} [9]. The discovery of such a particle could not be explained by the classical $q\bar{q}$ model. However, it would not be a proof of the existence of glue, since other systems, like $qq\bar{q}\bar{q}$ or $q\bar{q}g$, can have the same exotic J^{PC}.

Anyway, no candidates of that kind have yet been observed and the search is mainly turned toward the lowest mass states, with J^{PC} equal to 0^{++}, 0^{-+} and 2^{++}.

Glueball production

The safest theoretical prediction on glue concerns the way to produce it. The arguments are qualitative and come from perturbative Q.C.D. They favor processes where the expected gluonic state cannot share quarks with the other particles involved. There are different ways to get that situation :

- by construction :

a) in decays like $c\bar{c}$ or $b\bar{b} \rightarrow g+X$ (1), where X has a mass too low to contain b or c quarks

b) in reactions of the type $a+b \rightarrow a+b+X$ (2), where X is produced by two pomerons exchange and is nearly at rest in the centre of mass of a and b

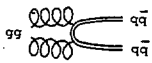
- by selection of special decay channels :

c) in the reaction $\pi^- + p \rightarrow n+X$ (3) followed by the decay $X \rightarrow \phi\phi$, the $\phi\phi$ system contains only s and $\bar{s}$ quarks, absent in the π^-, the proton and the neutron. This reaction is said to violate the O.Z.I. rule[10].

In the following, we will mainly concentrate on the process (1) applied to the 1^{--} ground state of the charmonium, the $J/\Psi(3097)$, where a lot of experimental results are available.

Widths and decays

The widths of the lower lying states depend on the coupling of glue to the world of quarks. It could be less than the width of the ordinary mesons with the same quantum numbers, which are allowed to decay directly[11]. For instance, (α) contains two $q\bar{q}g$ coupling absent in (β) .

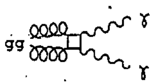
(α) 

(β) 

In fact, the diverging character of this coupling at low momenta forbids, for the time being, safe predictions, even for pure glue states.

Excited glue states can decay into other glue states and are likely to be wider[11].

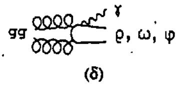
The partial width into two photons would be zero in a world without quarks, since gluons are not sensitive to the electro-magnetic interaction. It is given by the box diagram (γ) where the gluons to photons coupling is obtained through a quark loop. At first sight, this process leads to $\gamma\gamma$ widths one order of magnitude below the $\gamma\gamma$ widths of ordinary mesons [12], but, as for the total widths, the non perturbative aspect of the strong interaction weakens the prediction[13].



(γ)

The fact that glue is flavourless should give the clearest criteria to recognize it in hadronic decays. The coupling gluon-quark is indeed the same for all flavours, and if one neglects the mass differences between the u, d and s quarks, all the decays of glue are left unchanged by any permutation of them. On the contrary, the decays of $q\bar{q}'$ states keep memory of the initial flavours. For instance, after correction of phase space effects, the three branching ratios ($gg \rightarrow \rho\rho$, $\omega\omega$ or $\phi\phi$) are equal, whereas ($s\bar{s} \rightarrow \rho\rho$ or $\omega\omega$) and ($u\bar{u} \pm d\bar{d} \rightarrow \phi\phi$) are forbidden by the O.Z.I. rule[10]. Similarly, for 0^{++} and 2^{++} gluonic mesons, one expects comparable rates into pseudoscalar pairs $\pi\pi$, $K\bar{K}$ and $\eta\eta$.

For the same reason, if they are accessible to the experiment, the radiative modes (δ) have rates respectively proportional to $(q_u-q_d)^2/2$, $(q_u+q_d)^2/2$ and q_s^2, that is to say 9, 1 and 2, since they only differ by the the mean electric charge of the quarks in the vector meson.



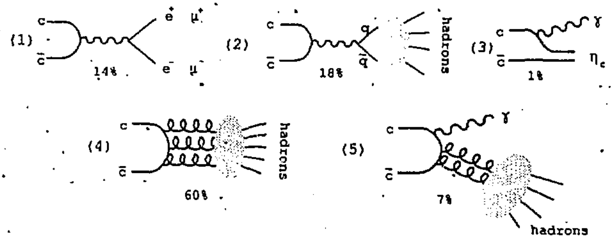
Otherwise, all the decay modes allowed by phase space and conservation laws exist a priori[14]. It can be noticed that the decays of the $\eta_c(2980)$, pseudoscalar ground state of the $c\bar{c}$ system, should look much like the decays of a two gluons state, since it is a flavour SU(3) singlet that decays through two gluons[15]. Today, about only 20% of its decays are known, among which $p\bar{p}$ and $\phi\phi$, which are, as expected, comparable[16].

The theoretical approach of the mass region from 1 to 2 GeV/c^2 is still lacking in precision, which is due to the non perturbative aspect of the strong interaction and to the lack of experimental data to test the models. The experimental approach must then be as wide as possible. Gathering information is needed to evidence this new state of matter.

II. EXPERIMENTAL APPROACH

1. The J/Ψ, a source of gluonic mesons

The J/Ψ(3097), discovered in 1974, is the lower lying $c\bar{c}$ vector meson. Its mass is below the threshold of open charm production, which gives it remarkable properties. An ordinary 3 GeV meson would have a width of several hundred MeV, whereas the J/Ψ width is only 63 keV. Electromagnetic interactions play an important part in its decays which are described by the following five diagrams :



where the percentages are the approximate rates of each type of decay, (2) and (4) being supposed not to interfere. This description neglects graphs with more than three gluons.

Radiative decays, as described by diagram (5), produce a two gluons system with an invariant mass spectrum extending from 0 to 3 GeV/c^2.This system has a positive charge conjugation, because both the J/Ψ and the photon have negative charge conjugations. For on shell gluons, the spin-parity of this system splits up in fonction of its mass as shown on figure 4, computed from first order Q.C.D.[29]

Spin-parity 2^+ dominates, the 0^+ and 0^- components are equal and there is a small contribution of 4^+ at low masses.

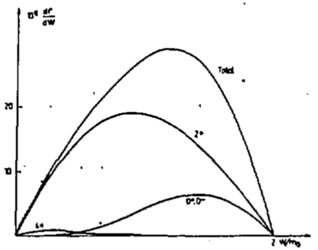


Fig. 4.

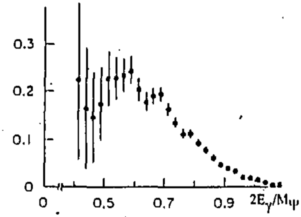


Fig. 5.

With massive gluons, there are additional 1^{++} [30] and 1^{-+} [31] components.

This two gluon system is expected to be strongly coupled to the two gluon bound states of same quantum numbers and less coupled to ordinary mesons with positive charge conjugation and zero isospin[28]. The radiative decays of the J/Ψ are therefore a potential source of scalar, pseudoscalar and tensor glueballs. Moreover, as it will be shown in the next paragraph, the important rate of these decay modes favors their experimental study.

2. Calculation of the radiative decay rate

The J/Ψ decays description by processes (1) to (5) allows an evaluation of the inclusive branching ratio $(J/\Psi \to \gamma X)$. This description uses the fact that processes (1) to (3) are known from experiment, and that graphs (4) and (5) are both related to (1) by the theory.

- The processes (1), $J/\Psi \to e^+e^-$ and $J/\Psi \to \mu^+\mu^-$, have been measured[17]. Both branching ratios amount to 6.9 ± 0.9 %. As they must be equal, up to terms of the order of $(M_\mu/M_\Psi)^2$ [18], the error on their value becomes $0.9/\sqrt{2} = 0.64$ %.

- (2) is related to (1) through the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ whose value is $2.59 \pm 0.15 \pm 0.08$ [19] at 3 GeV center of mass energy.

- The decay (3) towards the η_c has a rate of 1.27 ± 0.36 %[20].

- The processes (4) and (5) have been calculated at the time of the discovery of the J/Ψ in first order Q.C.D. They are both proportional to (1). The corresponding relations are :

$$\Gamma_{\Psi \to 3g} = \frac{5(\pi^2-9)}{18\pi}\,\frac{\alpha_s^3}{\alpha^2}\,\Gamma_{\Psi \to \mu\mu} \qquad \text{(a)}$$ [21],

and

$$\Gamma_{\Psi \to \gamma gg} = \frac{16}{5}\,\frac{\alpha}{\alpha_s}\,\Gamma_{\Psi \to 3g} \qquad \text{(b)}$$ [22].

When neglecting the interference between (2) and (4) and the effect of higher order processes, we get :

$$(\Psi \to \gamma\eta_c) + (\Psi \to e^+e^-) + (\Psi \to \mu^+\mu^-) + (\Psi \to q\bar{q}) + (\Psi \to 3g) + (\Psi \to \gamma gg) = 100\ \%,$$

where the parentheses stand for branching ratios.

Using the preceeding relations, one gets

$$(1.27 \pm .36)\ 10^{-2}+(6.9 \pm .6)\ 10^{-2}.[2+(2.59 \pm .17)+\frac{5}{18}\,\frac{\pi^2\text{-}9}{\pi}\,\frac{\alpha_s^3}{\alpha^2}\,(1+\frac{16}{5}\,\frac{\alpha}{\alpha_s})] = 1 \qquad \text{(A)}$$

which gives the following equation in α_s: $\alpha_s^3 + 2.34\ 10^{-2}\,\alpha_s^2 = (6.74 \pm 0.90)\ 10^{-3}$ (B)

hence $\underline{\alpha_s(M\Psi) = 0.181 \pm 0.008 \text{ and } (J/\Psi \to \gamma gg) = 7.[illegible] \pm 0.4\ \%.}$

which, if true, is very precise. Actually, we have used two different kinds of approximations which could considerably alter the result :

- the effect of higher order terms in α_s in the perturbative development of Q.C.D. must be examined,

- relations (a) and (b) are obtained in a non relativistic approximation. The relativistic effects[25] involve corrections of the order of $\langle v^2 / c^2 \rangle$ (= 0.2 at the J/Ψ) which have not yet been precisely computed[24] but which are probably important for relation (a) and small for relation (b).

The next perturbative order in α_s gives additionnal terms[25] :

$(10.2 \pm 0.5)\ \alpha_s(M_\Psi) / \pi$ to the $\Gamma_{\Psi \to 3g} / \Gamma_{\Psi \to \mu\mu}$ ratio

and $(4.4 \pm 0.4)\ \alpha_s(M_\Psi) / \pi$ to the $\Gamma_{\Psi \to \gamma gg} / \Gamma_{\Psi \to 3g}$ ratio.

Equation (B) is now :

$$\alpha_s^3(1+(10.2 \pm .5)\alpha_s/\pi) + 2.34\ 10^{-2}\,\alpha_s^2(1+(4.4 \pm .4)\alpha_s/\pi) = (6.74 \pm .90)\ 10^{-3}$$

and its solution is $\alpha_s = 0.159 \pm 0.006$, only 12% lower than the value obtained at first order. The radiative branching ratio is even less affected by this correction, since the lowering of α_s is balanced by the additional positive term in the $\Gamma_{\Psi \to \gamma gg} / \Gamma_{\Psi \to 3g}$ ratio. It amounts now to (7.0±0.4)%. The result is therefore stable against the Q.C.D. radiative corrections. A few remarks can be made on this subject.

$\alpha_s(Q^2)$ is measured here in the time-like region and its Q^2 dependence is probably not the same as in the space-like region, where diffusion processes take place[26]. Its low value is compatible with the other existing measurements[70].

As the sum of all perturbative orders is directly related to physical quantities, the second order calculation depends on the choice of a renormalisation scheme. Several ways have been investigated to find a scheme that minimizes the contribution of the non computed higher order terms[24]. The result presented uses the standard MS scheme. Another convention, the so called "effective charges" or FAC scheme[27] chooses the renormalisation point which cancels the second order correction. It leads to $\alpha_s(M_\Psi) = 0.15 \pm 0.01$ and to the same branching ratio as in the first order calculation.

To avoid the relativistic corrections, the relation (b) where they are supposed to cancel can be associated with the measurement (Ψ→3g)+(Ψ→γgg) = 6±3 %. $\alpha_s(M_\Psi)$ has now to be known.

With Λ_{QCD}= 200±100 MeV, $\alpha_s(M_\Psi)$=.21±.04, (b) gives (Ψ→3g)/(Ψ→γgg) = .11±.02 and the radiative branching ratio amounts to 6.6 ± 1.1%, which is very close to the preceding values.

If the Q.C.D. second order correction is now included in (b), with the same value for $\alpha_s(M_\Psi)$, $(J/\Psi \rightarrow \gamma gg) = 5.2 \pm 1.0\%$. Again, the result is quite stable.

The conclusion of this discussion is that neither the Q.C.D. higher orders, nor the relativistic corrections have a large effect on the naive first order prediction. Taking these corrections into account, one gets :

$$\boxed{(J/\Psi \rightarrow \gamma gg) = 6 \pm 2\%.}$$

This calculus can be also applied to the *Υ(9460)* which is the analog of the *J/Ψ* for the $b\bar{b}$ system. But, in this case, the ratio of the partial widths into γgg and 3g is 4 times lower than for the J/Ψ because the charge of the b quark is half the charge of the c quark. In spite of this lower rate, the radiative decays of the Υ potentially produce gluonia and high statistics analyses would extend this study to masses higher than 3 GeV/c^2.

3. Inclusive measurements

e^+e^- allows high statistic studies of J/Ψ decays, one month of data taking corresponding to about one million J/Ψ (1MΨ) produced on the existing machines (about 3MΨ on DCI). The J/Ψ has been studied in Hamburg on DORIS by PLUTO and DASP, in Stanford on SPEAR by MARK I, MARK II, CRYSTAL BALL (2.2 MΨ) and MARK III (5.7 MΨ) and in Orsay on DCI by DM2 (8.6 MΨ).

MARK II[32)] has given an inclusive measurement of the radiative mode. Such an analysis suffers from a large background which comes from hadronic decays with π^0's or η's. Due to detection inefficiencies, the decays of π^0 and η to two photons can simulate isolated photons. This background has been separately measured and subtracted from the energy spectrum of the whole set of photons. The spectrum is shown on figure 5.

For $E_\gamma < .6\ M_\Psi/2$, the result is not precise. For $E_\gamma > .6\ M_\Psi/2$, or $M_X < 2$ GeV/c^2, the branching ratio of the process $J/\Psi \rightarrow \gamma X$ amounts to $4.1 \pm .8\%$, near to the expected rate for the whole spectrum.

CRYSTAL BALL has analyzed the radiative modes with more statistics and a better photon energy resolution. The lower granularity of this detector makes it more difficult to extract the π^0 and η backgrounds. On the inclusive spectrum shown on figure 6, only several classes of non radiative events have been removed, and the masses lower than about 500 MeV/c^2 have been cut out[2)].

This spectrum shows structures that have been studied in exclusive analyses.

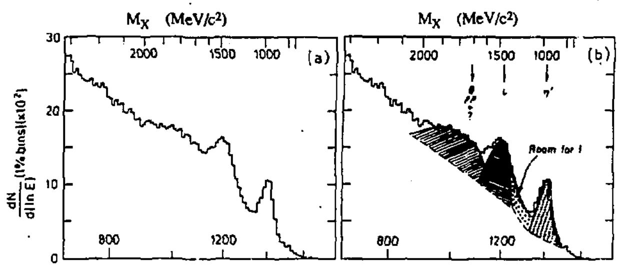


Fig. 6a. E_γ (MeV)

Fig. 6b. E_γ (MeV)

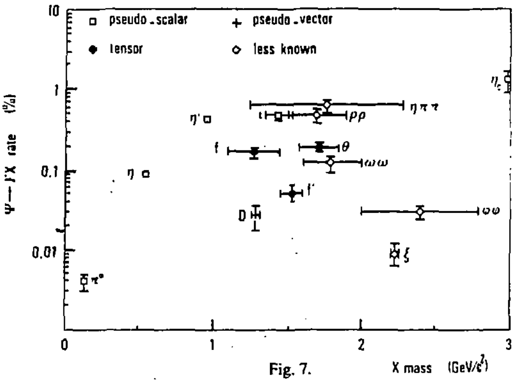


Fig. 7.

4. Exclusive measurements

Figure 7 shows the present status of exclusive studies on J/Ψ radiative decays.

Most of them will be discussed in the following. The old names of particles have been used to simplify the figure. ι stands for η(1440), D for $f_1(1285)$, f for $f_2(1270)$, θ for $f_2(1720)$ and f' for $f'_2(1525)$.

On figure 6b, the η(1440) and η' are seen with large and comparable rates, which is confirmed on figure 7. The $f_2(1720)$ and the wide states seen in ρρ and ηππ can explain the excess of events between 1.6 and 2. GeV/c^2.

The most copiously produced states are a priori the best glueball candidates.

There is yet no measurements on scalar mesons.

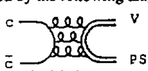
Except for the η_c, the sum of all measured radiative branching ratios amounts to 2.6±.4%. There is some room left for yet unmeasured processes, if the theoretical prediction or the MARK II inclusive measurement are to be taken at face value.

5. Glue component in the η'

The η' mass is much higher than that of the other members of the pseudoscalar nonet (π, K and η). It is very abundant in the radiative decays of the J/Ψ. These two properties could be related to the presence of a glue component in the η'.

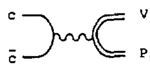
There are several ways to determine its wave function[33]. One of them is based upon the coupled analyses of all the J/Ψ decays into one vector (V) and one pseudoscalar (PS). These decays can be described by the following diagrams :

(a)



hadronic

and (b)



electromagnetic

in which the vector and the pseudoscalar must have the same flavour content.

The vectors are the ρ, ω, ϕ and K^* and the pseudoscalars are the π, η and η'. The vector nonet is supposed to be ideally mixed (the ϕ is a pure $s\bar{s}$) and the nonet symmetry is supposed to be conserved. So, only the $s\bar{s}$ component of the pseudoscalars couples to the ϕ, which forbids the $\phi\pi^0$ decay. Similarly, the ρ and ω select the u and d quarks in the pseudoscalars.

The ten possible channels are $\phi(\eta$ or $\eta')$, $\omega(\pi^0, \eta$ or $\eta')$, $\rho(\pi, \eta$ or $\eta')$, $K^{*\pm} K^{\mp}$ and $K^{*0} K^0$.

The calculation in the SU(3) framework depends on the 8 following parameters :

- one amplitude for the electromagnetic term,

- two amplitudes for the hadronic term (one conserves flavour SU(3), the other breaks it through a mass term),

- one phase between the electromagnetic and the hadronic terms,

- the four (X,Y) components of the η and η' on the states $|N\rangle = 1/\sqrt{2}|u\bar{u}+d\bar{d}\rangle$ and $|S\rangle = |s\bar{s}\rangle$[35].

MARK III measured 9 of these modes and set limits on $\phi\pi^0$ and $\rho\eta'$. The 8 parameters have been optimized according to the 9 branching ratio values. The χ^2 probability is 14% and the result is :

$$\underline{X_\eta^2+Y_\eta^2 = 1.1 \pm 0.2 \text{ and } X_{\eta'}^2+Y_{\eta'}^2 = 0.65 \pm 0.18 .}$$

So, the η wave function is saturated by a mixing of two states $|N\rangle$ and $|S\rangle$, whereas the 2σ effect on the η' implies with a 97% probability the presence in it of an extra state which will be called $|G\rangle$ in the following discussion.

Besides, this analysis finds out that the electromagnetic term contributes for about 10%, the same as for the general decays of the J/Ψ.

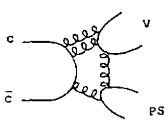
The decay into $\rho\eta'$ has been seen by DM2[68] and its branching ratio is in agreement with what is expected from this analysis.

Discussion

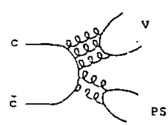
- This result assumes that all measurements are independent. It would not be the case if systematics errors on different channels were correlated. The values could then be slightly wrong and the errors underestimated.

- This description does not take into account the "simply" and "doubly disconnected" diagrams (c) and (d) which couple the singlet components of V and PS without flavour correlation :

(c)



(d)



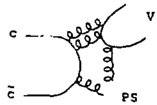
The absence of the $\phi\pi^0$ mode is only due to the nonet symetry and the absence of a mixing between ϕ and π^0 that would give them a common flavour component[36]. It is not an argument against the presence of disconnected diagrams since (c) and (d) can produce only zero isospin particles.

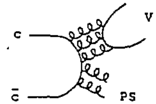
Recent analyses of the same kind[67], including diagram (c) and assuming that there are no extra components in the η and η', fit well the data and lead to a η - η' mixing angle in good agreement with current values[71]. The contribution of diagram (c) is found to be as large as the electromagnetic decay (b) in the case of the η' which has an important isosinglet component. Some theoretical predictions go in the same direction[37,38]. So, if there is any extra component in the η', it is certainly smaller than in the above analysis.

- The extra $|G\rangle$ that saturates the η' wave function could be of gluonic or $q\bar{q}$ nature. The third physical state involved in the $|N\rangle, |S\rangle, |G\rangle$ mixing could be the $\eta(1440)$[36].

If $|G\rangle$ is an excited $q\bar{q}$ state, then the interference between the ground and excited states in the production diagrams (a) and (b) has to be destructive. For instance, with $|\eta'\rangle = X_{\eta'}|N\rangle + Y_{\eta'}|S\rangle + Z_{\eta'}|G\rangle$, $|G\rangle$ being of the $|N\rangle$ type, $|X_{\eta'}+Z_{\eta'}|^2 + Y^2_{\eta'} = 0.65 \pm 0.18$ and with $X^2_{\eta'}+Y^2_{\eta'}+Z^2_{\eta'}=1$ it follows that $|X_{\eta'}+Z_{\eta'}|^2 < |X_{\eta'}|^2 + |Z_{\eta'}|^2$.

If $|G\rangle$ is of gluonic nature, this analysis assumes that it does not couple to the vectors. If this is true for diagrams (a) and (b), this is less sure for (c) and (d). Indeed, if the coupling to a $q\bar{q}$ pair on the PS side is removed, the V can be produced together with a two gluon bound state :





This mechanism, which would be responsible for the production of glue associated with an ω or a ϕ in the decays of the J/Ψ, has not been calculated yet.

- This approach can be seen as an exercise on the η and η'system. It is recent and can be improved on both theoretical and experimental sides. A better measurement of all V+PS channels would help to go further.

6.Coupled study of $J/\Psi \to (\gamma, \omega, \phi) + X$

The preceeding study can be applied to other particles than the π^0, η or η'. If a particle X is observed in the radiative mode, it can be searched for in association with an ω or a ϕ. If X is a pure gluonic meson, $J/\Psi \to \omega X$ and $J/\Psi \to \phi X$ can only proceed through disconnected diagrams. Their branching ratios are then expected to be smaller than for $J/\Psi \to \gamma X$ in which X is strongly coupled to the gluon pair. If X is a mixing of components (X_x, Y_x, Z_x) in the basis $(|N\rangle, |S\rangle, |G\rangle)$, where $|G\rangle$ is a glue state, then, the disconnected diagrams being neglected, $\Gamma(J/\Psi \to \omega X)$ is proportional to X^2_x (and independent of Y_x and Z_x), $\Gamma(J/\Psi \to \phi X)$ is proportional to Y^2_x, and $\Gamma(J/\Psi \to \gamma X)$ is an unknown function of (X_x, Y_x, Z_x).

If, in the picture of §5, only the main contribution (i.e. the SU(3) conserving hadronic term) is taken into account, then $\Gamma(J/\Psi \to \phi X)/\Gamma(J/\Psi \to \omega X) = Y^2_x/X^2_x$ up to kinematical terms that probably do not differ too much between the two modes.

This naive first order picture relates the Y_x/X_x ratio very directly to experimental measurements. It can be applied to the data on J/Ψ decays from MARK III and DM2. Up to now, nine particules have been looked for in association with a photon, an ω or a ϕ . Figure 8 shows the results.

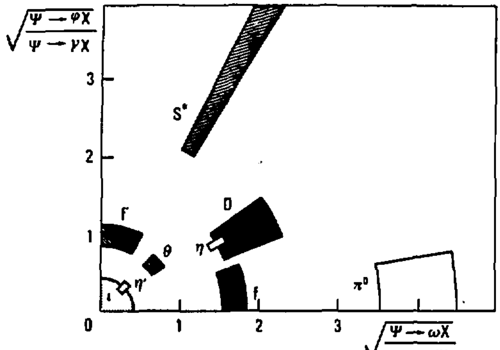


Fig. 8.

In this figure, the mean polar angle θ of each particle is such as tg θ = Y_x/X_x and the square of the mean radius is the ratio

$$\frac{\Gamma(J/\Psi \to \phi X) + \Gamma(J/\Psi \to \omega X)}{\Gamma(J/\Psi \to \gamma X)}$$

which measures the ratio of the X couplings to $q\bar{q}$ pairs and to gluon pairs. This ratio is expected to be small for gluonic mesons.

As in figure seven, the old names of particles have been used. S^* stands for $f_0(975)$, D for $f_1(1285)$, f for $f_2(1270)$, θ for $f_2(1720)$, f' for $f'_2(1525)$ and ι for η(1440).

If the disconnected diagrams were important, all particles would be aligned on the first diagonal (θ = 45°).

This simple picture agrees with our present knowledge on these particles :

- $X_{f'}$ and Y_f are compatible with zero as expected, since the f' is nearly a pure |S⟩ and the f nearly a pure |N⟩.

- The η and η' positions are near the first diagonal, which is coherent with the pseudoscalar mixing angle that gives them comparable X and Y[37].

This analysis brings also new informations on the $f_0(975)$ and the $f_1(1285)$ which can no more be considered as pure |N⟩ or |S⟩ states.

The comparison of the radial positions contains also information. For instance, the η(1440) and η' are near the origin, where glue is suspected to be.

This naive description which seems to work well can be improved. The angular analysis would give the contribution of S, P and D waves in each decay and allow to calculate the kinematical terms involved in the branching ratios. This would give better values for the Y_x/X_x ratios. The apparently weak contribution of disconnected diagrams has to be theoretically explained. Theoretical predictions of Γ(J/Ψ→γ,ω,φ+X) for known $q\bar{q}$ mesons could allow a deeper understanding of the meaning of figure 8.

In the next paragraphs, the experimental results leading to this coupled study are shown in more details. Most of these results come from the MARK III and DM2 experiments, which generally agree remarkably. The data of these two experiments were taken from 1982 to 1985. The radiative channels have been first analysed. The two other studies are more recent (1985 for the ϕ and 1986 for the ω) because they are associated to more complex final states ($\phi \rightarrow K\bar{K}$ and $\omega \rightarrow \pi^+\pi^-\pi^0$).

A coupled analysis of the decays $J/\Psi \rightarrow (\rho, K^*)+X$ would give the same kind of informations on non zero isospin states.

7. $X \rightarrow K\bar{K}\pi$

Figure 9[39] shows the mass spectra of $K\bar{K}\pi$ systems associated with the photon, the ω and the ϕ as measured by MARK III. The $\eta(1440)$, originally called ι and discovered by MARK II[40], is seen in the radiative spectrum. It is the most abundantly produced particle in the J/Ψ radiative decays and this is the reason why it was the first glueball candidate. It is a pseudoscalar[41] with the following mass and width parameters :

$$\underline{M=1458\pm5 \text{ MeV/c}^2 \text{ and } \Gamma=100\pm10 \text{ MeV/c}^2.}$$

The comparison between the three channels is more complex than expected.

The absence of signal associated with the ϕ proves that the potential $s\bar{s}$ component in the $\eta(1440)$ is small. Actually, at the 90% confidence level, one gets :

$$\frac{\Gamma(J/\Psi \rightarrow \phi\,\eta(1440))}{\Gamma(J/\Psi \rightarrow \gamma\,\eta(1440))} < 4\%.$$

On the contrary, a state X is seen against the ω ; its parameters are incompatible with those of the $\eta(1440)$. Its mass and width are smaller, its $K\bar{K}$ mass spectrum is not as peacked at low values and the angular analysis favours a non zero spin[42]. Restricted to the $K\bar{K}\pi$ decay channel, $\Gamma(J/\Psi \rightarrow \omega X)$ is about 15% of $\Gamma(J/\Psi \rightarrow \gamma\,\eta(1440))$.

According to the above defined criteria and notations, X is likely to be a $q\bar{q}$ state of the $|N\rangle$ type. It could be part of what is called $\eta(1440)$ in the radiative mode.

Then, at least some fraction of the $\eta(1440)$ fits the glueball selection criteria which have been defined above. If it is really a gluonic meson, it must be observed into other decay channels, for instance $\eta\pi\pi$, $K\bar{K}\pi\pi$, 4π. The $\eta\pi\pi$ mode is especially expected because the $\eta(1440)$ decay into $K\bar{K}\pi$ seems to be dominated by the intermediate state $a_0(980)\pi$ which gives $\eta\pi\pi$ when the $a_0(980)$ decays into $\eta\pi$.

8. $X \rightarrow \eta\pi\pi$

The first study of the $J/\Psi \rightarrow \gamma\eta\pi\pi$ channel has been done by the CRYSTAL BALL. Instead of the expected $\eta(1440)$, it showed a large production of a broad resonance (cf. fig.7) without dominance of the $a_0(980)\pi$[43] decay. MARK III and DM2 confirm this result with more statistics and they show that this strong $\eta\pi\pi$ production is not due to only one resonance.

The present limit on the $\eta(1440)$ branching ratio into $\eta\pi\pi$ has been given by part of the MARK III statistics. The limit is $\Gamma(\eta(1440) \rightarrow \eta\pi\pi) / \Gamma(\eta(1440) \rightarrow K\bar{K}\pi) < .2$,at the 90% confidence level. The angular analysis of the $\eta\pi\pi$ system would probably lower this limit[44].

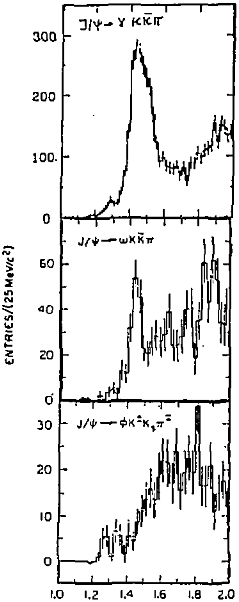


Fig. 9. M(KK̄π) GeV/c²

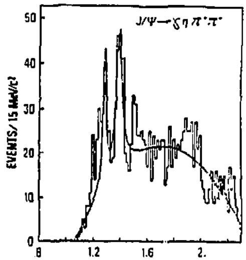


Fig. 10. M(ηππ) GeV/c²

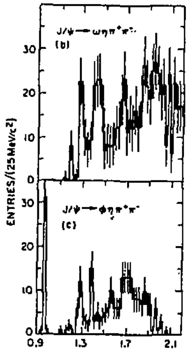


Fig. 11. M(ηππ) GeV/c²

The ηππ suppression is not well understood at present. A possible explanation could be the destructive interference in this mode between ηε and $a_0(980)\pi$, the only contribution to $K\bar{K}\pi$ coming from $a_0(980)\pi$. Actually, even the $a_0(980)\pi$ dynamics of the $K\bar{K}\pi$ channel is not conclusive.

Figure 10 shows the DM2 ηππ mass spectrum with one $a_0(980)$ required in the ηπ masses. The $f_1(1285)$, which is also seen in the channel $J/\Psi \to \gamma 4\pi$, is probably seen. The two measurements of $J/\Psi \to \gamma f_1(1285)$ from DM2 are consistent[46] and in good agreement with the perturbative Q.C.D. predictions for pseudovectors[30].

Another peak is found with a width of about 50 MeV/c² and a mass of 1391±3 MeV/c². It corresponds to a yet unknown particle which may have been recently observed in a $\pi^- p$ experiment at KEK[69]. In the ηππ decay mode, the branching ratio for $J/\Psi \to \gamma X(1390)$ is an order of magnitude below the branching ratio of $J/\Psi \to \gamma\eta(1440)$ in the $K\bar{K}\pi$ mode. This X state could be looked for in the $K\bar{K}\pi$ mode with an $a_0(980)$ cut on the $K\bar{K}$ mass, however, it is probably small compared to the η(1440) signal.

Several other structures can be guessed at higher masses, due to the very similar spectra from MARK III and DM2. To learn more about them, a full angular analysis would be necessary. Such an analysis has been attempted by MARK III on part of the statistics[44]; it is very difficult, especially due to the large background. Nevertheless, if it is done on the whole statistics, it might bring new results. For instance, the $\eta(1275)$, which has to be confirmed, might be hidden under the $f_1(1285)$ peak.

Figure 11, from MARK III, shows the production associated with an ω and a ϕ. The $f_1(1285)$ is seen again, with rates comparable with the radiative one (cf.fig.8). The X(1390) is absent. In its place, coupled to the ω, appears as in the $K\bar{K}\pi$ mode a state around 1420 MeV/c^2 with a width of about 50 MeV/c^2. This state could be the $f_1(1420)$ known as a $q\bar{q}$ pseudovector[39].

9. $X \to \eta\eta$

This channel has been studied by only one experiment[12], CRYSTAL BALL, which discovered there the $\theta(1650)$[47]. The θ was later seen in the $K\bar{K}$ mode on the right side of the $f'_2(1525)$[48], with a higher mass than in the $\eta\eta$ mode. After that, CRYSTAL BALL improved its analyses and explained its $\eta\eta$ signal by the presence of both the $f'_2(1525)$ and the θ, called now $f_2(1720)$. The corresponding mass spectrum is shown on figure 12.

CRYSTAL BALL also studied the $\eta\eta'$ mode and set the limit

$$\Gamma(f_2(1720) \to \eta\eta') \,/\, \Gamma(f_2(1720) \to \eta\eta) < .63$$

that favours an isosinglet $f_2(1720)$ since the $\eta\eta'$ combination is pure octet[11]. Anyway, the obervation of $f_2(1720) \to \eta\eta'$ with an important rate would have favoured its interpretation as a gluonic meson[49].

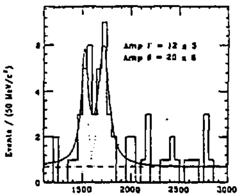


Fig. 12. M($\eta\eta$) MeV/c^2

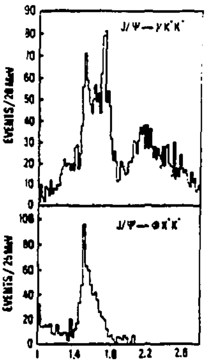


Fig. 13. M(K^+K^-) GeV/c^2

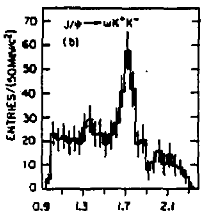


Fig. 14. M(K^+K^-) GeV/c^2

10. X→KK̄

This mode is at present time the dominant decay mode of the $f_2(1720)$. Its full angular analysis has been made by MARK III and DM2. The $f_2(1720)$ is clean and it counts a few hundreds of events. However, the conclusions of the angular analysis are not clear : the 2^{++} hypothesis is less favoured against the 0^{++} hypothesis than expected from the simulation of a 2^{++} state produced with the helicity parameters found for the $f_2(1720)$.

This fact might mean that, as the $\theta(1650)$ was the superposition of the $f'_2(1525)$ and the $f_2(1720)$, the $f_2(1720)$ could be a superposition of two or more states with different angular distributions. The present statistics does not allow to separate them.

If, as it will be the case in the following, the $f_2(1720)$ is considered as one particle, its helicity parameters are very different from those of the $f_2(1270)$ and the $f'_2(1525)$. This gives a place apart to the $f_2(1720)$.

Figure 13 from DM2[46] compares the radiative and the $\phi K\bar{K}$ channels. In the last one, the right shoulder of the $f'_2(1525)$ can be interpreted as the $f_2(1270)$ if both particles are allowed to interfere.

On figure 14 from MARK III[39], the $f_2(1720)$ is produced alone against the ω. The $f'_2(1525)$ is absent because it is nearly a pure $s\bar{s}$ state (cf.fig.8).

These measurements lead to suspect the presence of u, d and s quarks in the $f_2(1720)$. However, several arguments plead for a glue component in this meson :

- the comparison of the three branching ratios $J/\Psi \to (\gamma,\omega,\phi)+f_2(1720)$ shows that the $f_2(1720)$ is produced more strongly in association with a photon than with an ω or a ϕ (cf.fig.8),

- its decays show the flavour symmetry expected for a gluonic meson : its decay into $\pi\pi$[51] may have been observed and its decay rates into $\pi\pi$, $K\bar{K}$ and $\eta\eta$ would be respectively proportional to 1, 4 and 1,

- the present limit on the photon-photon width of the $f_2(1720)$ is small ; it is due to TASSO which gives $\Gamma(f_2(1720) \to K\bar{K})\,\Gamma_{\gamma\gamma}(f_2(1720)) < 0.28$ keV[52].

The $f_2(1720)$ has been unsuccessfully looked for in pion and kaon exchange experiments ($\pi^- p \to K\bar{K}n$ and $K^- p \to K\bar{K}\Lambda$) where a large signal was expected due to its important partial width into $\pi\pi$ and $K\bar{K}$. The absence of a signal could be explained if a large part of the $f_2(1720)$ decay modes had up to now escaped to analysis[53], which is unlikely.

On the contrary, signals have been seen in the $f_2(1720)$ mass region in the $\pi\pi$[54] and $K\bar{K}$[55] channels in central production experiments, and in $\eta\eta$ in the reaction $\pi^- p \to \eta\eta n$[56].

11. X→ππ

The scalar gluonic mesons masses are the lowest predicted ones[7]. They could be around 1 GeV/c^2. The dominant decay mode should be $\pi\pi$. This is where they have been searched for.

The charged mode study is impossible below 1 GeV/c^2 as shown on the DM2[50] figure 15, due to a very large background around the $\rho^\circ(770)$ mass. This background comes from the very abundant decay $J/\Psi \to \rho^\circ\pi^\circ$ where the π° can decay into an asymmetrical photon pair. Then the photon that carries almost all the π° momentum mimics perfectly the radiative photon of the decay $J/\Psi \to \gamma\pi^+\pi^-$ and the other one has a too low energy to be detected.

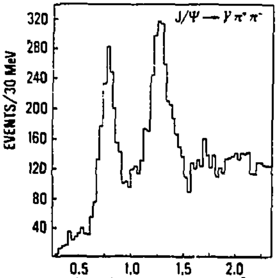


Fig. 15. $M(\pi^+\pi^-)$ GeV/c²

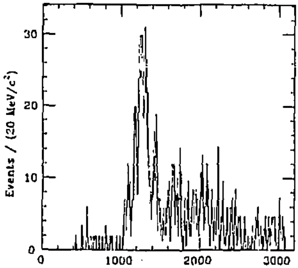


Fig. 16. $M(\pi^0\pi^0)$ MeV/c²

The channel $J/\Psi \to \gamma\pi^0\pi^0$ does not suffer from this background because $\rho^0 \to \pi^0\pi^0$ is forbidden by C-conservation. The best limit has been given by CRYSTAL BALL in this all neutral decay[72]. Figure 16 shows the $\pi^0\pi^0$ mass spectrum. The dominant signal is as in the charged decay mode due to the $f_2(1270)$. This detector cannot study the $\pi^0\pi^0$ masses below 500 MeV/c² for which, in most cases, the four photon showers are merged. The limit, for a state between 500 and 1000 MeV/c², with a width smaller than 100 MeV/c², is :

$$\underline{(J/\Psi \to \gamma X \to \gamma\pi^0\pi^0) < 1.3\ 10^{-5}.}$$

This limit is very strong compared to the measured radiative branching ratios (cf.fig.7). It seems to exclude totally the existence of a gluonic meson between 500 and 1000 MeV/c². However, it is worth recalling that the two gluon system produced in the radiative decay of the J/Ψ is weakly coupled to the low mass scalars (cf.fig.4), which can explain the low $f_0(975)$ radiative production.

Besides, a narrow glueball candidate has been claimed in an interpretation of data on $\pi\pi$ and $K\bar{K}$ production by two pomeron exchange[59]. This positive result might not be in contradiction with the CRYSTAL BALL limit.

There are no limits for masses below 500 MeV/c² where anyway no gluonic mesons are expected, and for masses over 1000 MeV/c² where much more statistics would be necessary to extract a scalar particle from the other present signals. A full angular analysis of the whole mass spectrum would be useful, particularly to get sure that the signal around 1700 MeV/c² is really due to the $f_2(1720)$.

The shape of the right shoulder of the $f_2(1270)$ is not well fitted by a Breit-Wigner. The full angular analysis of the $\pi^+\pi^-$ spectrum confirms the presence around 1440 MeV/c² of a narrow object with helicity parameters very different from those of the $f_2(1270)$[73]. This fact cannot be explained by the presence of the $f'_2(1525)$ interfering with the $f_2(1270)$ because both particles have similar angular distributions.

The $\pi^+\pi^-$ spectra associated to an ω and a ϕ, coming from DM2, are shown on figures 17 and 18[46]. In the $\phi\pi^+\pi^-$ mode, the $f_0(975)$ is clearly seen. Its shape is affected by the opening of the $K\bar{K}$ channel. It does not fit with a Flatté distribution but it is well described by a final state interactions model optimized on $\pi\pi$ phase shift data, which relates these apparently disconnected fields[74].

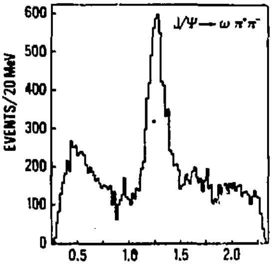


Fig. 17. M($\pi^+\pi^-$) GeV/c^2

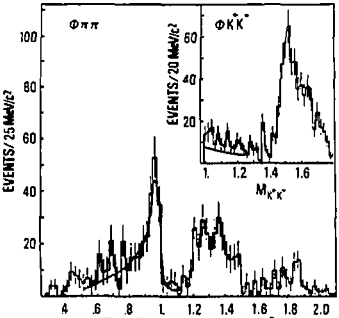


Fig. 18. M($\pi^+\pi^-$) GeV/c^2

The enhancement at low $\pi\pi$ masses in the $\omega\pi\pi$ channel can be explained in the Q.C.D. framework[75].

The $f_2(1720)$, seen in the channels $\omega K\bar{K}$ and $\gamma\pi\pi$[51] should appear in the $\pi\pi$ spectrum produced against an ω. Its observation would give a cross check of these analyses. For the time being, the background level is too high to draw conclusions.

12. $X \rightarrow \phi\phi$

Two pion diffusion experiments on protons[60] (fig.19) and on Beryllium[61] (fig.20) have observed wide resonances decaying into $\phi\phi$ pairs with masses between 2. and 2.4 GeV/c^2.

The argument for their gluonic nature is the fact that the O.Z.I. rule is violated in their production(cf.I.4). In fact, all their characteristics can be explained if they are interpreted as mixings of two 2P excited states of the $|N\rangle$ and $|S\rangle$ type, $|S\rangle$ being dominant[62].

A signal has been observed in the same decay channel in the radiative decays of the J/Ψ. Figure 21 shows the DM2 spectrum[63]. A part of this production is compatible with 2^{++} and the branching ratio of the process $J/\Psi \rightarrow \gamma\phi\phi$ for masses below 2.9 GeV/c^2 is about $3.\ 10^{-4}$.

It can be attempted to relate the two observation, but the present statistics on the J/Ψ decays is two small to draw conclusions. Nevertheless, these states must be looked for in other decay modes, for example $\rho\rho$ and $\omega\omega$ which have been studied and $\eta'\eta'$ and $K^*\bar{K}^*$ which have not.

13. $X \rightarrow \rho\rho$ and $X \rightarrow \omega\omega$

The study of these two channels in the radiative mode has been made by MARK III[64,65] and DM2[50,46]. Figure 22 shows the DM2 multi-channel analysis of the process $J/\Psi \rightarrow \gamma 4\pi^{\pm}$. Figure 23 shows the MARK III $\omega\omega$ signal.

Both analyses show the presence of structures between 1.6 and 2. GeV/c^2. The low mass peak at about 1.6 GeV/c^2 can be attributed to the $\eta(1440)$ distorted by the presence of the $\rho^\circ\rho^\circ$ mass threshold[66]. If this interpretation is correct, it gives one more argument for the gluonic nature of the η'1440).

On part of its data, MARK III set limits of a few 10^{-4} on the branching ratios to the $\rho\rho$ and $\omega\omega$ 2^{++} projections between 2.1 and 2.4 GeV/c. The $\phi\phi$ branching ratio being of the same order of magnitude, these limits don't tell more about the $\phi\phi$ states.

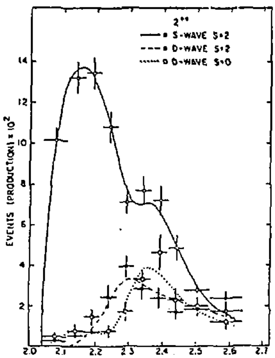


Fig. 19. M($\phi\phi$) GeV/c^2

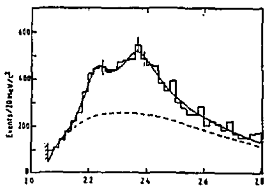


Fig. 20. M($\phi\phi$) GeV/c^2

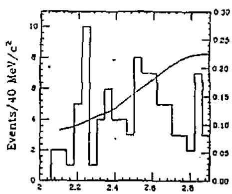


Fig. 21. M($\phi\phi$) GeV/c^2

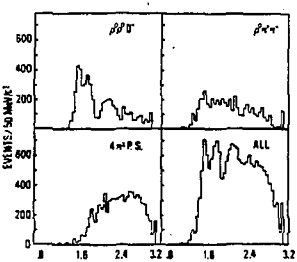


Fig. 22. M($4\pi^{\pm}$) GeV/c^2

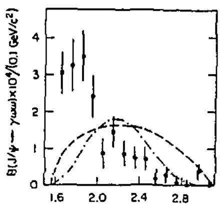


Fig. 23. M($\omega\omega$) GeV/c^2

Conclusions

If the gluonic mesons are firmly predicted by theory, their theoretical and experimental search is not an easy task. It is strongly related to the $q\bar{q}$ spectroscopy in the 1 GeV/c^2 mass region, which has not yet been fully explored. It needs gathering information on the candidates by :

- the study of all the accessible decay channels,

- the diversification of experimental approaches,

- the clarification of glueball signature criteria.

The J/Ψ decays play in this search an important part. They give to the same experiment access to all the possible decay channels. Many new states are seen, particularly the η(1440) which fills all the conditions required to be a gluon bound state. The present analyses of MARK III and DM2 leave many questions unsolved. A new generation of experiments will have to answer them, with higher statistics and better angular acceptance to allow the separation of the different partial waves in every channel.

Acknowledgements

This course was originally prepared for the 1986 Gif-sur-Yvette school in France. I thank the organizers of this workshop for the opportunity they gave me to present it in Erice. I thank for their help and advice during the preparation and the writing G. Mennessier, F.M. Renard, M. Fontannaz and A. Le Yaouanc for the theory, J. Lefrançois and L. Fayard for the $p\bar{p}$ minijets part, the DM2 collaboration members and especially B. Jean-Marie and G. Szklarz for the experimental aspect, with a special thank to J.E. Augustin who directed this work.

I thank Ms. H. Blattmann, A. Pottier and N. Mathieu for the practical realisation and G. Szklarz and B. Le Treut for the reading of the english translation.

References

1. H. Fritzsch, M. Gell-Mann, Proceedings of the XVI International Conference on High Energy Physics, Chicago-Batavia, Illinois, Vol.2, 135 (1972).

2. E.D. Bloom, comptes rendus de la 21ème Conférence Internationale de Physique des Hautes Energies, Paris, France, JOURNAL DE PHYSIQUE, C3-407 (1982).

3. B. Dieckman, CERN EP/86-112 ;
J.E. Augustin, Proceedings of The Quark Structure of Matter, Strasbourg-Karlsruhe, 323 (1985) ;
J.E. Augustin, Proceedings of Physics in Collisions 5, Autun, France, 243 (1985) ;
N. Wermes, Proceedings of Physics in Collisions 5, Autun, France, 221 (1985) ;
S. Cooper, Proceedings of the International Europhysics Conference on High Energy Physics, Bari, Italy, 945 (1985)

4. F. Cerapibi, Proceedings of the 23rd International Conference on High Energy Physics, Berkeley, California (1986).

5. L. Di Lella, Ann. Rev. Nucl. Part. Sci., 35, 107 (1985).

6. R.P. Feynman, Les Houches, 121 (1976) ;
J. Iliopoulos, CERN 76-11 ;
E. De Rafael, Ecole de Gif, tome 2 (1978).

7. S.R. Sharpe, A.I.P., Conf. Proc. n°121, 1 (1984).

8. M.S. Chanowitz, Proceedings of the Summer Institute on Particle Physics, SLAC-245, 41 (1981).

9. S. Meshkov, to be published in Proceedings of the Aspen Winter Physics Conference, (1986).

10. S. Okubo, Phys. Lett. 5, 165 (1963) ;
G. Zweig, CERN TH-401 et TH-402 (1964) ;
J. Iizuka, Prog. Theor. Phys. Supp. 37-38, 21 (1966).

11. F. Renard, unpublished paper refering to :
H.J. Lipkin, Phys. Lett. 109B 326 (1982) ;
J.M. Cornwall, A. Soni, Phys. Lett 120B 431 (1982) ;
J.J. Coyne, P.M. Fishbane and S. Meshkov, Phys. Lett. 91B, 259 (1980).

12. H. Kolanoski, Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, Japan, 90.

13. J.F. Donoghue, Phys. Rev. D30, 114 (1984) ;
M.S. Chanowitz, Proceedings of the VI International Workshop on Photon-Photon Collisions, Lake Tahoe, California, 95 (1984).

14. J.D. Bjorken, Proceedings of the International Conference on High Energy Physics (E.P.S.), Geneva, vol 1, 245 (1979)
J.F. Donoghue, A.I.P. Conf. Proc. n°81, 97 (1981).

15. E.D. Bloom, Proceedings of the Summer Institute on Particle Physics, SLAC-245, 1 (1981) ;
E.D. Bloom, C.W. Peck, Ann. Rev. Nucl. Part. Sci., 33, 143 (1983)
R. Barbieri et al., Phys. Lett 106B, 497 (1981) ;
T. Appelquist et al., Phys. Rev. Lett. 34, 365 (1975).

16. B. Jean-Marie, LAL 86/29, Proceedings of the 23rd International Conference on High Energy Physics, Berkeley, California (1986).

17. S.M. Boyarski et al., Phys. Rev. Lett. 34, 1357 (1975).

18. T.Appelquist, R.M.Barnett and K.Lane, Ann.Rev.Nucl.Part.Sci.,414 (1978).

19. J.L. Siegrist et al., Phys. Rev. D26, 969 (1982).

20. J.E. Gaiser, Thèse, SLAC-255 (1982).

21. T. Appelquist, H.D. Politzer, Phys. Rev. Lett. 34, 43 (1975).

22. M.S. Chanowitz, Phys. Rev. D12, 918 (1975).

23. W. Buchmuller, S.H.H. Tye, Phys. Rev. D24, 132 (1981).

24. D.W. Duke, R.G. Roberts, Phys. Rep. 120, 275 (1985).

25. P.B. Mackenzie, G.P. Lepage, A.I.P. Conf. Proc. n°74, 176 (1981).

26. M.R. Pennington, R.G. Roberts and G.G.Ross Nucl. Phys. B242, 69 (1984).

27. A. Grunberg, Phys. Rev. D29, 2315 (1984).

28. S.J. Brodsky et al., Phys. Lett. 73B, 203 (1978) ;
K. Koller, and T. Walsh, Nucl. Phys. B140, 449 (1978).

29. A. Billoire, R. Lacaze, A. Morel, H. Navelet, Phys. Lett. 80B, 381 (1979).

30. J.C. Körner et al., Nucl. Phys. B229, 115 (1983) ;
J.C. Körner et al., Zeit. f. Phys. C16, 279 (1983).

31. R. Lacaze, H. Navelet, Nucl. Phys. B186, 247 (1981).

32. D.L. Sharre et al., Phys. Rev. D23, 43 (1981).

33. J.L. Rosner, Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, Japan, 448 ;
J. Haïssinski, to be published in Proceedings of the VIITH Workshop on Photon-Photon Collisions, PARIS (1986).

34. R.M. Baltrusaitis et al. Phys. Rev. D32, 2883 (1985).

35. J.L. Rosner Phys. Rev. D27, 1101 (1983).

36. H.E. Haber and J. Perrier, Phys. Rev. D32, 2961 (1985).

37. H. Fritzsch and J.D. Jackson Phys. Lett. 66B, 365 (1977).

38. S.S. Pinsky, Phys. Rev. D31, 1753 (1985).

39. L. Köpke, Proceedings of the 23rd International Conference on High Energy Physics, Berkeley, California (1986).

40. D.L. Sharre et al., Phys. Lett. 97B, 329 (1980).

41. C. Edwards et al., Phys. Rev. Lett. 49, 259 (1982) ;
J.D. Richman, Ph.D., CALT-68-1231 (1985).

42. L. Köpke, XXIème Rencontre de MORIOND 2, 437 (1986).

43. C. Edwards et al., Phys. Rev. Lett. 51, 859 (1983).

44. J.J. Becker, Ph.D., University of Illinois at Urbana-Champaign (1984).

45. W.F. Palmer et al., Phys. Rev. D30, 1002 (1984) .

46. B. Jean-Marie, LAL 86/33, Proceedings of the 23rd International Conference on High Energy Physics,Berkeley,,California (1986).

47. C. Edwards et al., Phys. Rev. Lett. 48, 458 (1982).

48. M.E.B. Franklin, Ph.D., SLAC-254 (1982).

49. J.Schechter, Phys. Rev. D27, 1109 (1983) ;
S.S. Gerstein et al., Zeit. f. Phys. C24, 305 (1984).

50. J.E. Augustin et al., LAL/85-27.

51. K.F. Einsweiler, Ph.D., SLAC-Report-272 (1984) ;
D.M. Coffman et al., SLAC-PUB-3720.

52. M. Althoff et al., Zeit. f. Phys. C29, 189 (1985).

53. S. Cooper , Proceedings of the 23rd International Conference on High Energy Physics, Berkeley, California (1986).

54. T. Akesson et al., Nucl. Phys. B264, 154 (1986).

55. T.A. Armstrong et al., Phys. Lett. 167B, 133 (1986).

56. D. Alde et al., Nucl. Phys. B269, 485 (1986) ;
D. Alde et al., CERN EP/86-140.

57. R.A. Lee, Ph.D., SLAC-Report-282 (1985).

58. K. Wacker, XVIIIème Rencontre de MORIOND 2, 91 (1983).

59. K.L. Au et al., XXIème Rencontre de MORIOND 2, 455 (1986).

60. A.Etkin et al., Phys. Lett. 165B, 217 (1985).

61. P.S.L. Booth et al., CERN-EP 85-138 (1985).

62. S.Ono , O. Pene and F. Schöberl, Prog. Theo. Phys. 74, 545 (1985).

63. D. Bisello et al. Phys. Lett. 179B, 294 (1986).

64. R.M. Baltrusaitis et al., Phys. Rev. D33, 1222 (1986) ;

65. R.M. Baltrusaitis et al., Phys. Rev. Lett. D33, 1723 (1986).

66. N. Wermes, Proceedings of Physics in Collisions 5, Autun, France, 221 (1985).

67. A. Seiden, H.F.-W. Sadrozinsky, H.E. Haber, SCIPP 86/73 ;
H.F.-W. Sadrozinsky in Hadrons, to be published in Quarks and Gluons, Rencontres de Moriond 1987 ;
A. Falvard, to be published in Int. Eur. Conf. on High Energy Physics, Uppsala, Sweden (1987).

68. G.Szklarz, to be published in the 2nd Int. Conf. on Hadron Spectroscopy, Tsukuba,Japan (1987).

69. S. Fukui et al., contributed paper to the 2nd Int. Conf. on Hadron Spectroscopy, Tsukuba,Japan (1987).

70. see for instance F. Sciulli, Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, Japan, 7.

71.F.J. Gilman, R. Kauffman, Slac-Pub-4301 (1987).

72. This channel is being analysed by DM2 and results will appear in F. Couchot, Thèse d'état, to be published as a LAL report.

73. V. Lepeltier et al., LAL 87/10, submitted to Zeit. f. Phys.

74. G. Mennessier, Zeit. f. Phys. C16, 241 (1983).

75. H.G. Dosch and D. Gromes, HD-THEP-87-1, Heidelberg (1987).