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Some remarks on exotic mesons

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ABSTRACT. The fact that gluons carry color charge, makes the assumption of bound states of gluons, ggg, a fundamental prediction from quantum chromodynamics (QCD). Despite the search for these exotic mesons have revealed the existence of a large number of candidates, the unambiguous identification remains unsolved. The most recent experimental measurements in pp, πp, and $\bar{p}p$ interactions, from several experiments at FNAL, BNL, and CERN, have accumulated strong evidences of some well established candidates to exotic mesons. In this paper the experimental situation for the search for exotic mesons is discussed. The paper outline the experimental difficulties in the field and emphasizes the importance for QCD of the unambiguous identification of such exotic mesons. The paper emphasizes also the importance of the most recent and new measurements coming from experiments with high statistics in gluon-rich channels.

RESUMEN. El hecho de que los guones transporten carga de color, hace la suposición de estados ligados de gluones, ggg, una predicción fundamental de QCD. A pesar de que la búsqueda de estos mesones exóticos ha revelado la existencia de un gran número de candidatos, la identificación no ambigua permanece aún sin lograrse. Las más recientes mediciones experimentales en interacciones pp, πp y $\bar{p}p$, provenientes de varios experimentos en FNAL, BNL y CERN, han acumulado fuertes evidencias de algunos candidatos a mesones exóticos. En este artículo la situación experimental en la búsqueda de mesones exóticos es discutida. El artículo delinea las dificultades experimentales en este campo y enfatiza la importancia para QCD de la identificación no ambigua de tales mesones exóticos. El artículo enfatiza también la importancia de las más recientes y nuevas mediciones provenientes de experimentos con alta estadística en canales ricos en contenido gluónico.

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1. INTRODUCTION

The experimental confirmation of the existence of quarks became available more than two decades ago. Deep-inelastic scattering experiments of electrons on protons showed evidence of point-like constituents (quarks) inside the proton. A new type of charge called "color" was assigned to the quarks. The interaction between quarks is mediated by the exchange of a spin 1 particles called gluons, which have the notable property of carrying color charge as the quarks do. The field theory that governs the interaction between colored gluons and quarks is called quantum chromodynamics (QCD).

According to the quark model, quarks can be combined in two forms to produce all the known hadrons; that is, mesons are bound states of valence quark-antiquark pairs $q\bar{q}$ and baryons consist of three valence quarks qqq. However, due to the fact that gluons carry color charge, they can, in principle, interact among themselves to form bound states of gluons. Mesons composed entirely of valence gluons (gg or ggg) are called glueballs.

During the last two decades a major experimental effort has been made to find evidence for the existence of glueballs. In addition to glueballs, two new kinds of unusual mesons have been also proposed. These are bound states of valence quarks, antiquarks and gluons ($q\bar{q}g$), called hybrids, and four-quarks bound states $q^2\bar{q}^2$, called molecules. All these states are generally called exotic mesons or non-$q\bar{q}$ mesons.

In recent years there has been great activity in light meson spectroscopy, which not only has given the opportunity to study ordinary mesons, but to observe the existence of states which are candidates to be non-$q\bar{q}$. A confirmation of these states with more complicated inner structure will be an important test for QCD. In this paper the search for exotic mesons is discussed.

The most recent measurements mainly from Fermilab, BNL MPS, and CERN, have accumulated strong evidences of some well established exotic candidates and some gluon-rich processes.

The structure of this paper is the following: Sect. 2 is devoted to the discussion of general features of exotic mesons. Section 3 is concerned to some theoretical calculations of the mass spectrum for exotic mesons. In Sect. 4 are discussed experimental features concerned to the search for exotic mesons. Finally, in Sect. 5 it outlines the perspectives in the field, according to the most recent measurements.

2. General features of exotic mesons

Since the 1970's experimental evidence of the existence of a large number of mesons which do not fit to the schemes of the $q\bar{q}$ models has accumulated. Those mesons are states with unusual combinations of quantum numbers J^{PC} forbidden for hadrons with ordinary quark structure, or states with either anomalous decay channels, or unusual production modes.

According to the quark model neutral $q\bar{q}$ mesons with spin S and orbital angular momentum L have parity P and charge conjugation C given as [1]

$$P = -(-1)^L, \qquad C = (-1)^{L+S}. \tag{1}$$

Therefore, some combinations of quantum numbers are not allowed for the conventional $q\bar{q}$ mesons. The possible existence of mesons with quantum numbers forbidden, is interpreted as a strong evidence of the existence of mesons not contemplated in the quark model.

Table I shows that set of quantum numbers J^{PC} allowed for $q\bar{q}$ mesons up to $J = 4$ and the corresponding quantum numbers forbidden for $q\bar{q}$ states.

2.1. Glueballs

From a theoretical viewpoint glueballs are basic predictions of QCD [2]. Although the existence of a glueball spectrum is predicted by QCD, the prediction of glueball masses remains like an important challenge [2–4]. Glueball mass calculations are not reliable.

TABLE I. Set of quantum numbers J^{PC} allowed and forbidden for $q\bar{q}$ states up to $J = 4$.

J (spin)	J^{PC} allowed for $q\bar{q}$ states	J^{PC} forbidden for $q\bar{q}$ states
0	0^{++}, 0^{-+}	0^{+-}, 0^{--}
1	1^{++}, 1^{+-}, 1^{--}	1^{-+}
2	2^{++}, 2^{-+}, 2^{--}	2^{+-}
3	3^{++}, 3^{+-}, 3^{--}	3^{-+}
4	4^{++}, 4^{-+}, 4^{--}	4^{+-}

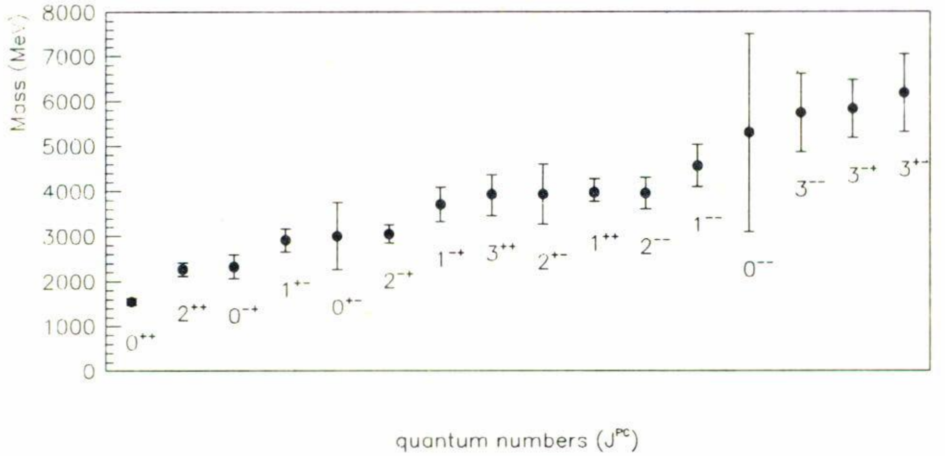

FIGURE 1. Spectrum predicted for glueballs (from Bali *et al.* 1993).

Some calculations show that the lowest scalar and tensor glueballs lie in the mass range of 1–2.5 GeV [3]. Other calculations show that glueballs are not light, giving values of $M_{0^{++}} = 1.5$ GeV for the lowest lying scalar glueball and $m_{2^{++}} = 2.3$ GeV for the tensor glueball. Figure 1 shows the predicted gluonic spectrum. Several theoretical models have been implemented to extract expectations of a gluonic spectrum; bag models in which the gluons are considered massless spin-1 particles [5], potential models with massive constituent gluons [6, 7], lattice gauge theories [8, 9], QCD sum rules [10–16], and flux tube model [17]. However, in all these models (in which variety is a signature of the complexity of the problem) there is some agreement that the lowest state expected in the gluonic spectrum is the scalar $J^{PC} = 0^{++}$ at around 1.5 GeV [18].

From the experimental point of view the situation is also inconclusive. Although there are several candidates for glueballs, there is not (yet) a conclusive confirmation.

2.2. *Hybrids*

Those states consisting of both quarks and gluons as constitutents are called hybrids. These states can have either unusual production and decay mechanisms or an exotic set of quantum numbers.

In the $q\bar{q}g$ system the $q\bar{q}$ must be in a color octet and the whole system $q\bar{q}g$ must be in a color singlet, with total angular momentum given by [19]

$$\mathbf{J} = \mathbf{j} + \mathbf{l} + \mathbf{s}, \tag{2}$$

where $\mathbf{j}$ is the angular momentum of the gluons, $\mathbf{l}$ is the orbital angular momentum of the $q\bar{q}$ and $\mathbf{s}$ is the sum of the quark spins.

Like glueballs, the study of the hybrid mass spectrum has also been carried out in the framework of several models such as bag model [20–23], QCD sum rule [24, 25], potential model [26] and flux tube model [17]. The general result of the spectroscopic studies from all these models is that the lightest hybrid mesons are below 2 GeV in mass [18]. In fact, according to the bag model the masses of the low-lying hybrid mesons are between 1.32 GeV and 1.87 GeV [23]. This mass region coincides with that expected for glueballs; so accordingly it has been suggested that hybrids are largely mixed with glueballs [20].

An important feature of these models is the prediction of a $q\bar{q}g$ state in the mass range between 1 GeV and 1.8 GeV, with quantum numbers 1^{-+} forbidden for a normal $q\bar{q}$ meson. Calculations from the bag model predict a 1^{-+} hybrid with mass between 1.4 GeV and 1.8 GeV, while the QCD sum rule model gives masses between 1 GeV and 1.3 GeV for that state.

Finally, $q\bar{q}g$ spectroscopy has hybrids heavier than the corresponding quarkonia by an amount of 0.7 GeV to 1.0 GeV, which is attributed to the effective gluon energy [27].

2.3. Molecules

The third class of non-$q\bar{q}$ states are weakly-bound four-quark mesons $q^2\bar{q}^2$, generally called hadronic molecules.

Two different interpretations have been given to the internal structure of multiquarks states. According to the bag model [28–31] multi-quark states exist as bound state of four quarks confined in a bag interacting via gluon exchange. On the other hand, in the potential model [32–36] the ground state of the $q^2\bar{q}^2$ system is treated as consisting of two weakly interacting mesons. In other words, $q^2\bar{q}^2$ bound state do not exist as resonances in this model. In fact, Weinstein and Isgur [32, 33, 36] have pointed out that the 0^{++} sector of this system with $K\bar{K}$ quantum numbers is probably the only exception in the potential model.

From the above claims it is clear that the theoretical predictions for the properties of these states are somewhat contradictories. However, some common signatures have been predicted for these multi-quark states [1, 29, 37, 38]:

1. Mass close to some important threshold, due to a binding energy of a most 50–100 MeV.
2. Large branching ratio to decay into corresponding hadronic constituents.
3. Total angular momentum $L = 0$, due to the short range of the nuclear forces that bind molecules.

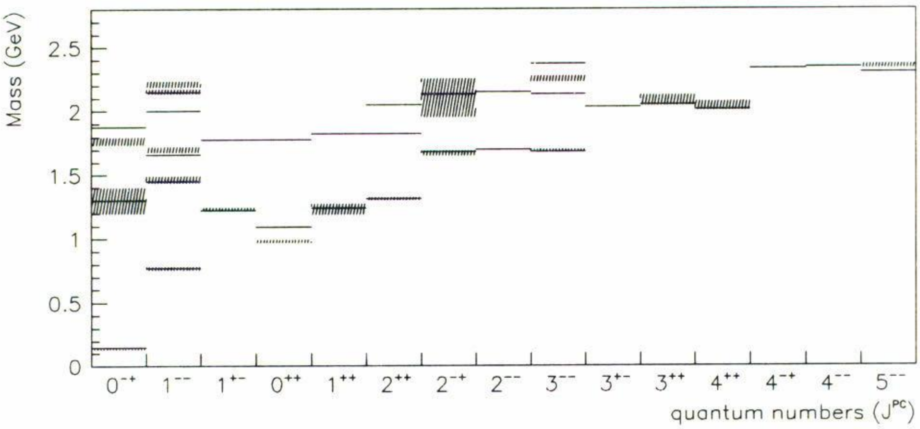

FIGURE 2. The isovector mesons. Solid lines represent the predicted masses of states according to the GI model. Shaded areas corresponds to the experimental masses and their uncertainties according to the PDG (1994).

3. THEORETICAL PREDICTIONS

A large number of theoretical models have been developed, from which can be extracted predictions about the mass spectrum for glueballs, hybrids, and molecules. Models such as bag model, potential model, and lattice gauge theory, includes different assumptions and have different expectations, which in some cases are somewhat contradictories.

3.1. The Godfrey-Isgur model

The present understanding of hadron structure is based on the quark model in which baryons are composed of three valence quarks and mesons are composed of a pair of valence quark-antiquarks. The spectroscopy of $q\bar{q}$ states is treated in several models inspired by QCD.

On the other hand, there exists general agreement that a high confidence signal of the existence of exotic mesons probably requires a better understanding of the spectrum of conventional $q\bar{q}$ mesons. In that sense, in 1985 S. Godfrey and N. Isgur [39] proposed a relativistic quark model (GI) which is able to describe with enough accuracy the $q\bar{q}$ meson spectrum from the π to the Υ. Because of its large range of predictions and its accuracy, this model is widely used to compare its predictions with the experimental findings and to test if a resonance belongs or not to some $q\bar{q}$ multiplet.

In this section we compare the predictions of the GI model with the experimental measurements as given by the Particle Data Group (PDG) [37]. Only the light meson sector is taken into account. Figures 2 thru 4 show the comparison for the isovector mesons ($I = 1$), the strange mesons ($I = 1/2$) and the isoscalar mesons ($I = 0$).

In Fig. 4 the states $f_j(1710)$, $X(1740)$ and $X(1950)$ appear in all the $J^{PC} = (\text{even})^{++}$ sectors; see the PDG (1994) [37].

From Figs. 2 thru 4 can be drawn two important conclusions; the first concerns the high level of confidence of the GI model predictions. The second is probably the most

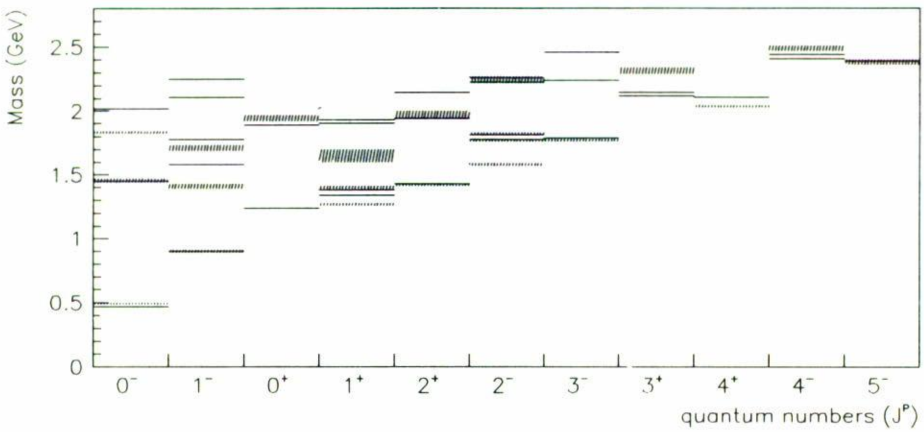

FIGURE 3. The strange mesons. Solid lines represent the predicted masses of states according to the GI model. Shaded areas correspond to the experimental masses and their uncertainties according to the PDG (1994).

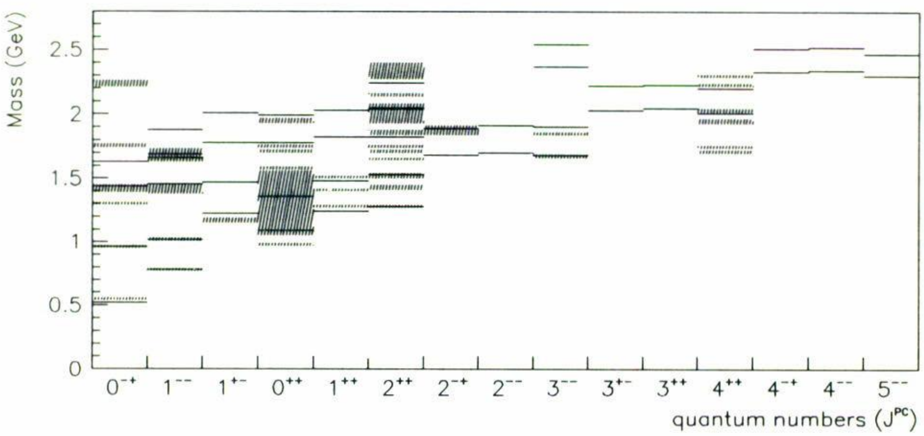

FIGURE 4. The isoscalar mesons. Solid lines represent the predicted masses of states according to the GI model. Shaded areas correspond to the experimental masses and their uncertainties according to the PDG (1994).

important result: seen are some states which appear to not have a place in the $q\bar{q}$ nonets of the quarkonium scheme. Figure 5 shows those isoscalar meson sectors in which there seem to be more states than those predicted by the GI model.

4. SEARCH FOR EXOTIC MESONS

The search for exotic mesons has played an important role in light meson spectroscopy over the last two decades. The search has involved several experiments and has led to the discovery of several candidates, although the results remain ambiguous.

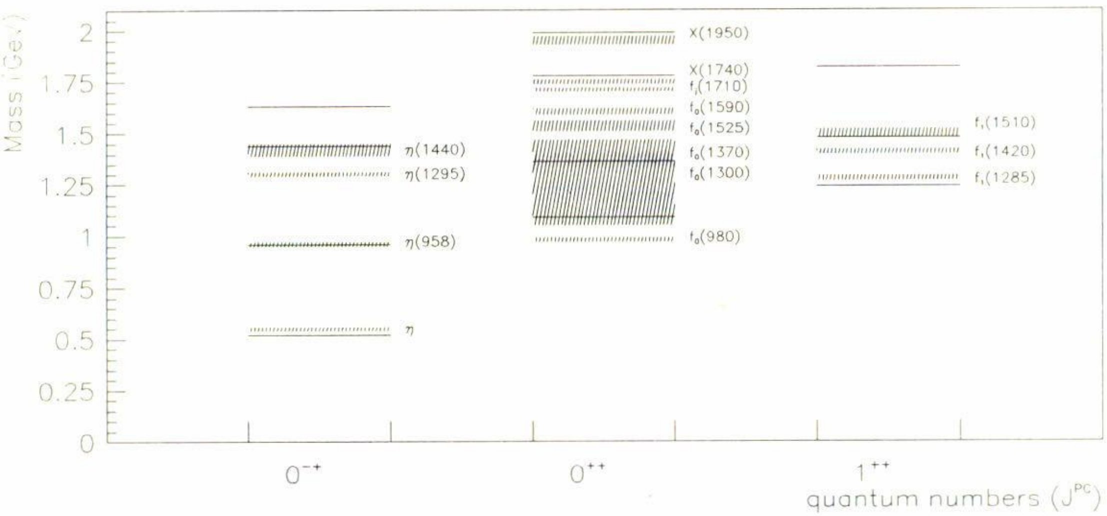

FIGURE 5. Isoscalar meson sectors with non-$q\bar{q}$ candidates. Solid lines represent the predicted masses of states according to the GI model. Shaded areas correspond to the experimental masses and their uncertainties according to the PDG (1994).

There are several reasons that complicate the direct identification of exotic mesons:

1. In the 1–2 GeV mass region where one expects to find the larger number of exotic mesons, there is a huge number of $q\bar{q}$ ground states which even overlap, in the same mass region, with their radial excitations.
2. The existence of "cryptoexotic" mesons [1]; that is, hadronic states that do not have exotic quantum numbers, and which have a complex internal structure that can only be established indirectly by examining particular features of their production and decay.
3. A big number of these mesons are expected to be very wide, 100–200 MeV [1], making it difficult to identify certain states.

However, it is expected that the non-$q\bar{q}$ mesons show certain common signatures which can contribute to their identification:

1. No place in $q\bar{q}$ nonets.
2. Exotic quantum numbers not allowed for $q\bar{q}$ states (in some cases).
3. Anomalies in either their production or decay modes.

The finding of states either having J^{PC} of an already completed nonet or having an exotic J^{PC} combination could be the most reliable signal for having found an exotic state.

4.1. No place in $q\bar{q}$ nonets

The first sign of the existence of exotic mesons comes precisely from the experimental observation of more states than those predicted by $q\bar{q}$ models.

In Fig. 5 is shown that:

(a) in the 0^{-+} meson sector from 1–1.5 GeV there is one state predicted by the GI model at 1.44 GeV and there are two observed, the $\eta(1295)$ and the $\eta(1440)$.

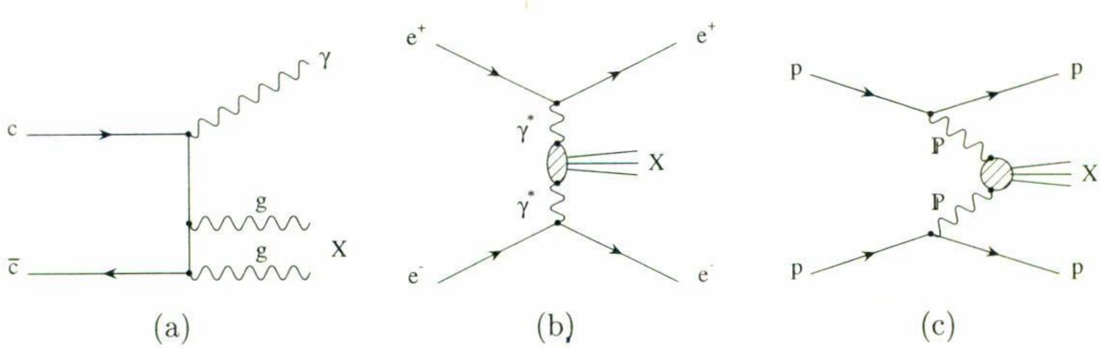

FIGURE 6. Different production mechanisms for non-$q\bar{q}$ mesons. (a) J/ψ radiative decay. (b) $\gamma\gamma$ interactions. (c) Double Pomeron exchange (DPE). The J/ψ radiative decay and the DPE are expected to be a source of gluonic states.

(b) In the 0^{++} meson sector from 0.9–1.8 GeV there are three states predicted at 1.09 GeV, 1.36 GeV, and 1.78 GeV and seven observed, the $f_0(980)$, $f_0(1300)$, $f_0(1370)$, $f_0(1525)$, $f_0(1590)$, $f_j(1710)$, and $X(1740)$.

(c) Finally, in the 1^{++} meson sector from 1–1.6 GeV there are two predicted at 1.24 GeV and 1.48 GeV and three observed, the $f_1(1285)$, $f_1(1420)$, and $f_1(1510)$.

Although in principle these 'extra' mesons are serious candidates to be non-$q\bar{q}$, the situation remains problematic. There are several questions not fully clarified; specifically some of these "extra" mesons have not been reliably established [1].

4.2. Exotic quantum numbers

The firmest evidence for having found an exotic meson would probably be the finding of a state with a J^{PC} combination forbidden for an ordinary $q\bar{q}$ meson, as given in Table I.

Up to now, only two states have been observed to have exotic quantum numbers. The first one is the $\hat{\rho}(1405)$, seen by GAMS [40] in $\pi^- p \to \eta\pi^0 n$ reactions. They claim to have observed a state with $J^{PC} = 1^{-+}$. However, this state needs confirmation [37]. Very recently, the MPS [41] Collaboration has published results of a spin-parity analysis of the reaction $\pi^- p \to f_1(1285)\pi^- p$, in which they found evidence of a broad $J^{PC} = 1^{-+}$ structure at 1.6–2.2 GeV. But again, their results are based on limited statistics, which required additional data for a more complete understanding of this state.

4.3. Production and/or decay mechanism

Other interesting evidences for having observed exotic mesons are either peculiar features or anomalies in their production and/or decay modes. A typical example of this is the $a_0(980)$, for which proper $q\bar{q}$ assignment remains a problem [37]. This state shows both a mass and width which seem to be incompatible with those expected for a member of a $q\bar{q}$ nonet.

Several theoretical models propose explanations for this state, but there is not general agreement. Some models have proposed a $q\bar{q}$ [42, 43] interpretation of the unusual features of the $a_0(980)$, while other ones interpret this state as a molecule [33, 44, 45].

TABLE II. Production mechanisms commonly used in the search for non-$q\bar{q}$ mesons.

Interaction	Reaction	Description
e^+e^-	$J/\psi \to \gamma X$	Mark II [46], Crystal Ball [47,48], and Mark III [49]. The J/ψ radiative decay is expected to proceed through a two gluon intermediate state [50]. See Fig. 6a.
	$J/\psi \to (\omega,\phi)X$	Mark III [51]. Like the J/ψ radiative decay, the J/ψ hadronic decay is useful in the investigation of the quark and possible gluonium content of a state X.
	$\gamma\gamma \to X$	TPC/Two-Gamma [52] and Mark II [53,54]. See Fig. 6b.
$\bar{p}p$	$\bar{p}p \to X$ at rest	Experiment using the Saclay hydrogen bubble chamber at CERN [55]. It was the first observation of a non-$q\bar{q}$ candidate.
Kp	$K^-p \to \Lambda X$	LASS [56] and Ref. [57]. Channels in K^- induced reactions are expected to be particularly rich in mesons with dominant $s\bar{s}$ quark content [56].
πp	$\pi^-p \to nX$	KEK [58], MPS [59], and an experiment using the hydrogen bubble chamber at CERN [60].
	$\pi^+p \to p(X)\pi^+$	WA76 [61].
pp	$pp \to p_s(X)p_f$	WA76 [61,62], E690 [63]. Centrally produced states via the double Pomeron exchange mechanism (DPE) are predicted to be a source of gluonic states [64]. See Fig. 6c.
πN	$\pi^-Be \to \pi X$	WA77 [65]. High p_T hadroproduction of mesons. The direct high p_T meson production via higher twist mechanism is expected to be an important source of gluonium [66]. It has been postulated also that gluonium states could be formed at high p_T in the fragmentation of gluon jets [67].
πd	$\pi^+d \to K_s^0K^\pm\pi^\mp X$	LASS [68].

Finally, the search for exotic mesons has been carried out in different production mechanisms. The existence of both higher statistics data and the diversity of measurements in different production mechanisms have meant a significant progress in recent years. In Table II are shown those production mechanisms commonly used. Figure 6 shows the different production mechanisms for non-$q\bar{q}$ mesons.

5. PERSPECTIVES

From the previous discussions it is clear that the unambiguous identification of an exotic meson in an unsolved problem, which remains a challenge.

However, the most recent data in gluon-rich production mechanisms like double Pomeron exchange (DPE) and J/ψ radiative decays, have revealed more convincing proofs of the existence of some well established non-$q\bar{q}$ meson candidates. In the same way, theoretical calculations from lattice gauge theory have beginning to be more consistent with the new measurements. Progress is such that the question of whether exotic mesons will be found may well be expected to be answered in the near future. Along this theoretical progress, the proposals for new high statistics experiments in several laboratories around the world, such as Fermilab, BNL, CERN, Beijing, and Cornell, provide an ideal opportunity to answer many questions still open in this field. It is expected that the new hadron spectroscopy facilities and the new experiments may contribute to shed light in the search for exotic mesons.

6. Conclusions

In recent years, the great activity in light meson spectroscopy, specifically in gluon-rich channels, have revealed a large number of mesons which cannot be accommodated within the conventional scheme of the quark model. However, despite those strong evidences, the unambiguous identification of non-$q\bar{q}$ mesons remains a challenge for the experimental high energy physics. It has became clear that much work still needs to be done to provide a convincing proof of the existence of a such exotic state.

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