

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Bari

INFN/AE-94/25
21 Ottobre 1994

Antimo Palano:

GLUEBALLS AND HYBRIDS: AN EXPERIMENTAL REVIEW

Invited talk to QCD 94, Montpellier, France, 7-13 July 1994

Servizio Documentazione
dei Laboratori Nazionali di Frascati

GLUEBALLS AND HYBRIDS: AN EXPERIMENTAL REVIEW

Antimo Palano

Dipartimento di Fisica dell'Università and Sezione INFN, Bari, Italy

ABSTRACT

In recent years, several new mesons have been discovered which are candidates for being exotic states. However, not all of them are sitting on solid experimental grounds. There are states which suffer from marginal statistics, others have not been observed in more than one experiment and still others have quantum numbers which are subject to drastic changes. This review is intended to perform a critical analysis of experimental status of gluonium and hybrids candidates.

1 INTRODUCTION

One of the most important expectations from QCD is the existence of gluonium (gg or ggg) and hybrid ($q\bar{q}g$) states. These mesonic resonances are expected to populate the low mass region (between 1.0 and 2.5 GeV) of the hadrons spectrum. Since this region is overpopulated by the standard $q\bar{q}$ mesons and their radial excitations, it is not easy to distinguish exotic from normal mesons. In addition, mixing between states with the same quantum numbers makes the task of identifying these states still more complicated. This could be the main reasons why, after about 15 years, the definitive existence of gluonium is still unproven. Simultaneously, theoretical predictions for these states have not made large progress, mainly due to the difficulty of calculating QCD in the confinement region.

Several experiments have given important contribution to the understanding of light meson spectroscopy and many new states have been *discovered* [1]. The production of resonances has been investigated in a large variety of interactions. Favorite processes where gluonium may appear are J/ψ decays [2] and central production [3] but it is also expected to see it in $p\bar{p}$ annihilations [4] and hadron interactions. Important inputs have also been given by $\gamma\gamma$ collisions [5] where, on the other hand, the production of glueballs is expected to be suppressed. Hybrids, on the other hand, could be produced in all these processes.

The strategy developed in the last few years in order to isolate exotic states is based on:

- a) comparing the production properties of a given new state in several physics reactions;
- b) the use of reactions and processes which can tag the flavour content or the quantum numbers of the produced states;
- c) comparing with the expectations from the quark model, for example the Godfrey-Isgur model [6] (in the following GI model).

An inspection of the Particle Data Group tables of mesons reveals a large variety of new resonances, too many from what expected from the quark model. Is this the evidence for gluonium? Unfortunately not because all these states follow a pattern and an overall scheme which is difficult to interpret. In addition, several of these states have undefined or still changing quantum numbers. Other states have been observed in only one experiment or even in particular kinematic ranges. Other resonances have short lifetimes: they live for some time and then disappear or change drastically their properties. All of this makes the work of phenomenologists rather hard and several of them, after having worked for some time inside this unstable world, have moved into more solide physics arguments. Are all these states real? How can we differentiate between true resonances and artefacts of data analysis?

We can try to apply some quality requirements to these results which can be summarized as follows. We can define a resonance as real if it satisfies the following requirements as far as possible:

- a) The resonance signal is observed directly in the mass spectrum;

- b) The state is observed with a high level of signal to background. In addition the experimental situation is not confused by the presence of several overlapping effects.
- c) The object is observed with high statistics.
- d) The state is seen by several experiments.
- e) A phase variation is observed.

We will apply these tests to the critical resonances candidates for being $non-q\bar{q}$ mesons in the different J^{PC} multiplets. The results of this analysis are summarized in table 1.

Table 1: *Status of exotic mesons candidates*

Particle	Signal visible	Small background	Large statistics	Several experiments	Phase variation	Status
$f_0(1400)$	possibly		yes	yes	yes	**
$f_0(1310)$			yes			*
$f_0(1520)$						*
$S^*/f_0(975)$	yes	yes	yes	yes	yes	***
$G/f_0(1590)$			yes		possibly	*
$AX/f_0(1520)$	yes		yes	yes		**
$\theta(1710)$	yes			yes		**
$f_2(1640)$	yes		yes	yes		***
g_T			yes		possibly	*
$\eta(1295)$			yes	possibly	yes	*
$\iota(1440)$	yes			yes		**
$E/f_1(1420)$	yes	yes	yes	yes		***
$f_1(1510)$	yes			yes		**
$\rho(1405)$			yes			*
$X(1450)$	yes		yes	possibly		**
$\xi(2200)$	possibly			possibly		*
$C/\rho(1450)$						*

2 SCALAR MESONS

Solving the scalar mesons puzzle is one of the most important problems in meson spectroscopy. The scalar glueball is, in fact, expected to be the lightest. It was predicted, for some time, around 1.0 GeV, but the latest lattice QCD calculations have moved its mass around 1.5 GeV. Its width, however, is uncertain so it could be so wide that it could escape detection. For these reasons the scalar mesons sector is one of the key areas where the gluonium problem could be solved.

The actual experimental situation of the mesons with $J^{PC} = 0^{++}$ is shown in fig. 1.

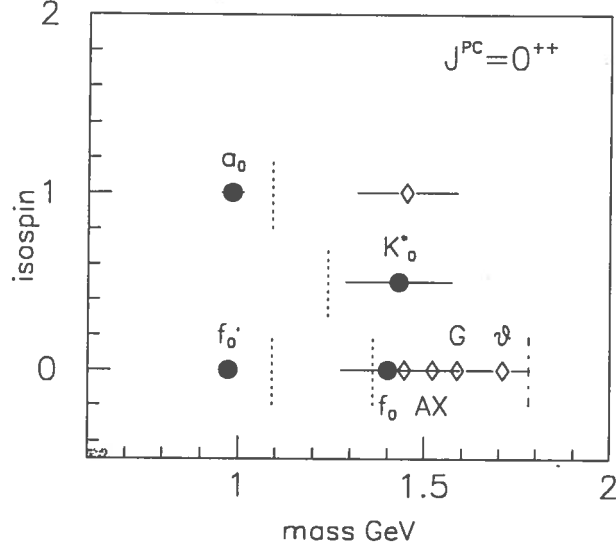


Figure 1: *Status of the scalar mesons. Symbols represent the experimental masses, horizontal bars their widths. Vertical bars represent the expectations from the GI model.*

The same figure also shows the expected masses from the GI model. An inspection of this figure reveals that the situation is actually rather confused and, in particular:

- i) The number of states far exceed the expectations from the quark model;
- ii) Even the existence of glueballs and hybrids can explain the presence of so many scalars.
- iii) The agreement with quark model is rather poor;
- iv) The number of scalar mesons strongly increases with time.

We can now try to apply the quality requirements to the most critical states and infer some information on the solidity of them.

2.1 Scalar mesons as possible artefacts from Partial Wave Analysis.

The evidence for scalar mesons could become very critical in experiments which suffer from limited geometrical acceptance. Mass spectra are populated by several overlapping resonances which are separated by using the angular informations through Partial Wave Analysis (PWA) algorithms. The standard procedure is to compute moments in the Gottfried-Jackson frame and then to evaluate the spin amplitudes from them. This last step require a system of equations with too many unknowns to be solved so that some assumptions are needed in order to solve all the mathematical ambiguities. Acceptance problems further complicate the method and the results from these analyses have to be viewed carefully, particularly in the extraction of the scalar amplitude. As an example of the above procedure, fig. 2 shows

the results from a PWA of the $K^+\pi^-$ system in the reaction $\pi^-p \rightarrow K^+\pi^-\Lambda/\Sigma$ at 10 GeV/c [7].

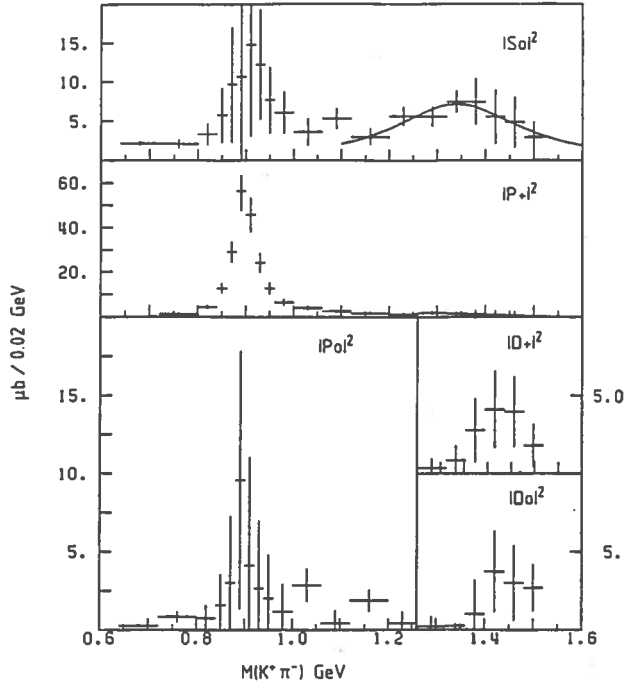


Figure 2: PWA of the $K^+\pi^-$ system in the reaction $\pi^-p \rightarrow K^+\pi^-\Lambda/\Sigma$.

The experiment was performed at the CERN- Ω spectrometer and made use of a trigger which selected a forward K^+ by means of a threshold Cherenkov counter. This selection created strong depletions in the angular distributions. Further assumptions were made in order to derive the amplitudes from the spherical harmonics moments. Finally one was left, in the K^{*0} region, with the following system of equations:

$$t_{00} = S_0^2 + P_+^2 + P_0^2 \quad (1)$$

$$t_{10} = 2S_0P_0 \quad (2)$$

$$t_{20} = 0.894P_0^2 - 0.447P_+^2 \quad (3)$$

$$t_{22} = -0.548P_+^2 \quad (4)$$

The critical point of this analysis is eq. 1, from which the scalar amplitude is derived. All the small systematic errors produced by the acceptance corrections and physical assumptions propagate to the S-wave. The result is a small but significant scalar wave which has the tendency to follow the strong resonances observed in the mass spectrum. In this particular example a peak well centered at the $K^{*0}(890)$ mass can be observed in the S-wave. This peak does not correspond to any real resonance but is just an artefact of the PWA.

How many of these effects could be present in the PDG which mimic resonances and further complicate the scalar mesons sector? Two possible examples are shown in fig. 3.

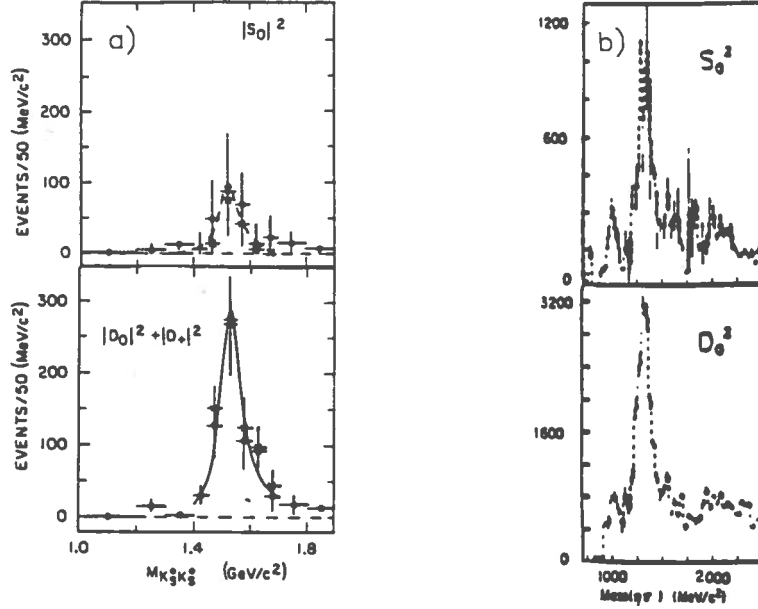


Figure 3: *Examples of scalar mesons placed below another resonance a) The $f_0(1520) \rightarrow K_S^0 K_S^0$ in K^- interactions from LASS, b) The $f_0(1310) \rightarrow \eta \pi^0$ in π^- interactions from GAMS. The scalar and tensor contributions are shown.*

Fig. 3a shows the evidence for $f_0(1520)$ in the reaction $K^- p \rightarrow K_S^0 K_S^0 \Lambda$ from LASS [8], fig. 3b shows the evidence for $f_0(1310)$ in the reaction $\pi^- p \rightarrow \eta \pi^0 n$ from GAMS [9]. Both scalar states are located below a much stronger spin 2 resonance, $f_2'(1525)$ and $a_2(1320)$ respectively.

A different case arises from ref.[10] at the CERN Ω -spectrometer. Here the centrally produced $2\pi^+ 2\pi^-$ mass spectrum shows a definite structure at 1.45 GeV on a large amount of background. The spin analysis of the $2\pi^+ 2\pi^-$ system is not easy to perform due to the presence of several intermediate states and by the presence of combinatorial problems. The scalar assignment to X(1450) could be due simply to a simplified spin analysis of a very complex experimental situation. The absence of a $\pi^+ \pi^-$ decay mode for this state is suspicious.

2.2 The $\pi\pi$ S-wave.

The $\pi\pi$ phase shift is shown in fig. 4a. Its features are understood (fig. 4b) as being due to the presence of a narrow structure ($S^*/f_0(975)$) superimposed on a broad effect ($\sigma(1000)$, $\Gamma = 700$ MeV).

Several experiments show evidence for yet another scalar resonance ($f_0(1400)$, $\Gamma = 350$ MeV). The existence of $f_0(1400)$ is rather well established from $p\bar{p}$ annihilations, central

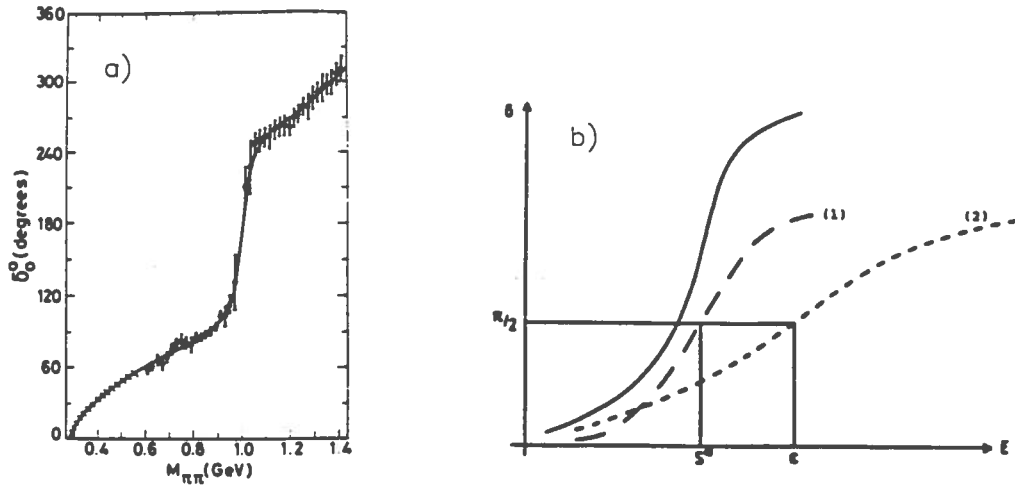


Figure 4: a) $\pi\pi$ phase shift from incident π^- beams. b) Its interpretation in terms of one narrow and one broad resonance.

production, J/ψ decays and $\gamma\gamma$ collisions, even if its parameters are somewhat different from one experiment to the other. The key problem here is the interpretation of the $\sigma(1000)$ effect. Some authors [11] in fact, point to this state as the $I=0$ non-strange member of the scalar mesons nonet, leaving $f_0(1400)$ as something else.

2.3 $S^*/f_0(975)$

The existence of this state is rather well established. Fig. 5 shows two examples of observations of this resonance: as a clear peak (even if distorted in shape) in the mass spectrum in J/ψ decay [2] and as a sharp drop in central production data [3].

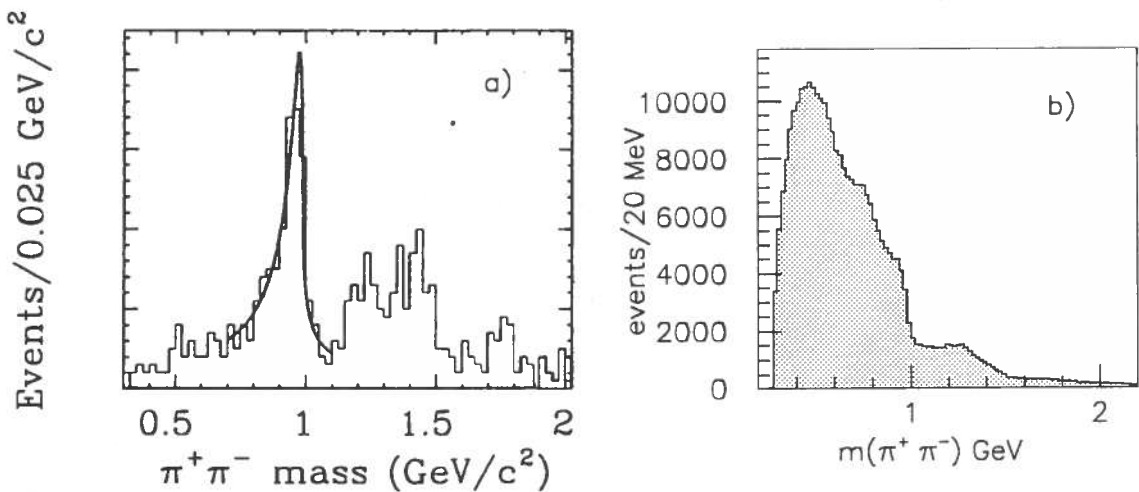


Figure 5: a) $\pi\pi$ effective mass from $J/\psi \rightarrow \phi(1020)\pi\pi$ (MarkIII). b) $\pi^+\pi^-$ effective mass from the reaction $pp \rightarrow p_f(\pi^+\pi^-)p_s$ at 300 GeV/c (Ω -WA76).

These features are understood as being due to the interference of $S^*/f_0(975)$ with the underlying $\pi\pi$ S-wave and to the proximity of the $K\bar{K}$ threshold.

This state is subject to a large interest due to the difficulties in understanding it in terms of a $q\bar{q}$ meson and to measure its properties. Its pole position is still moving significantly, even the exact number of poles contributing to this effect are uncertain. Important parameters to measure with good quality include the total width (presently it ranges from 30 to 72 MeV) and its $\gamma\gamma$ width. These measurements could help in distinguishing between the different hypotheses raised on the nature of this state: $q\bar{q}$ (mostly $s\bar{s}$), glueball, $K\bar{K}$ molecule and finally *minion*.

2.4 The $G(1590)$ meson.

This meson is on the ground, since about ten years, as a candidate for being the scalar glueball. It has been seen only by the GAMS experiment in a partial wave analysis of the $\eta\eta$ system in the reaction $\pi^-p \rightarrow \eta\eta n$ at 32 and 100 GeV/c [12]. The data at 100 GeV/c are shown in fig. 6.

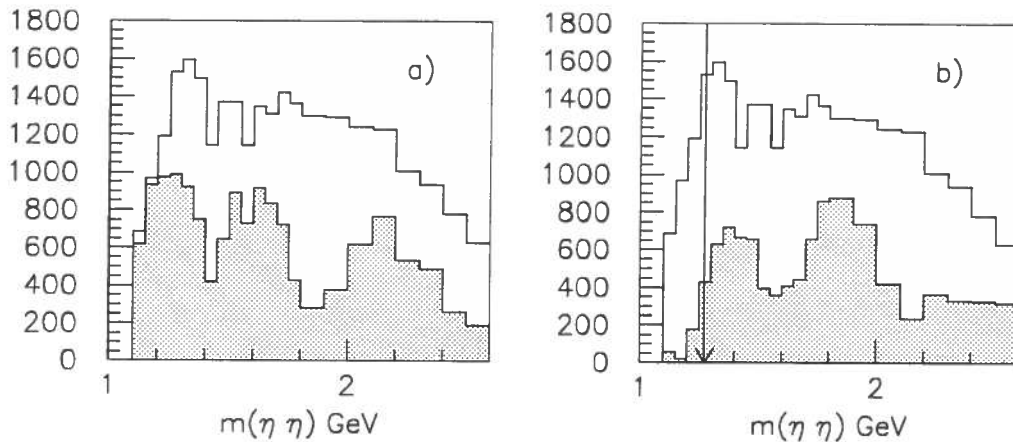


Figure 6: $\eta\eta$ mass distributions from incident π^- at 100 GeV/c. The shaded areas represent the a) scalar and b) the tensor contribution to the total cross section. The vertical line shows the position of the $f_2(1270)$. The data are from GAMS.

The mass spectrum shows a structure around 1.30 GeV, at the $f_2(1270)$ position. The PWA of the $\eta\eta$ system is affected, as usual, by two problems: a) the acceptance of the apparatus which is small at $\cos\theta_{GJ}$ close to one (exactly where spin 0 and spin 2 could be well discriminated) and b) by the problem of multiple solutions.

The spin 0 and 2 waves show several bumps, in particular the structure centered at 1.6 GeV is presented as evidence for $G(1590)$. However, one may also notice that the spin 2 wave shows a structure in the first part of the mass spectrum which should be due to $f_2(1270)$,

but shifted up in mass by about 100 MeV. Is this indicating a feedthrough between spin 0 and spin 2 waves?

Other decay modes do not help very much. The $\eta\eta'$ decay mode shows a threshold enhancement, while the $4\pi^0$ decay mode (fig. 7) does not show any clear structure in the $G(1590)$ region.

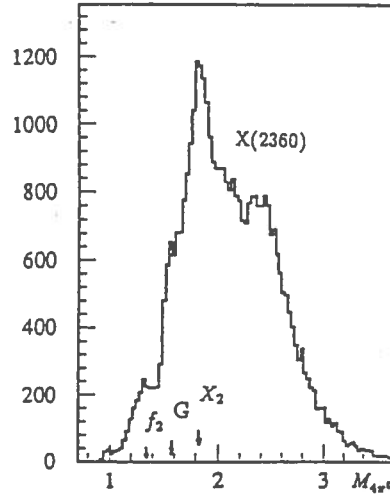


Figure 7: $4\pi^0$ effective mass in π^-p interactions. The data are from GAMS.

Evidence for $G(1590) \rightarrow \eta\eta$ in central production has been proposed. However, with increasing statistics the $\eta\eta$ mass spectrum shows a rather complex structure not resolved by a spin analysis. No evidence for this state is seen, by the same experiment, in the $\pi\pi$ decay mode.

In conclusion, the experimental status of this object is rather unstable and requires independent confirmation.

2.5 $AX/f_0(1520)$

The evidence for this state comes from the analysis of $\bar{p}p \rightarrow \pi(\pi\pi)$ data [13, 14]. The existence of a structure in this mass region is beyond any doubt (see 8).

However the number of states and the spin composition of the structure observed in the mass spectrum is not well established. This is mostly due to the complexity of performing spin analyses in $\bar{p}p$ annihilations where all the produced resonances interfere on the Dalitz plot producing structures and reflections which make hard to separate true resonances from reflections.

The spin of this state has been 2 for some time. However, a symultaneous analysis of the $\pi\pi$ and $\eta\eta$ system has recently moved its spin to 0. This has been largely due to a modification of the parametrization of the S-wave amplitude.

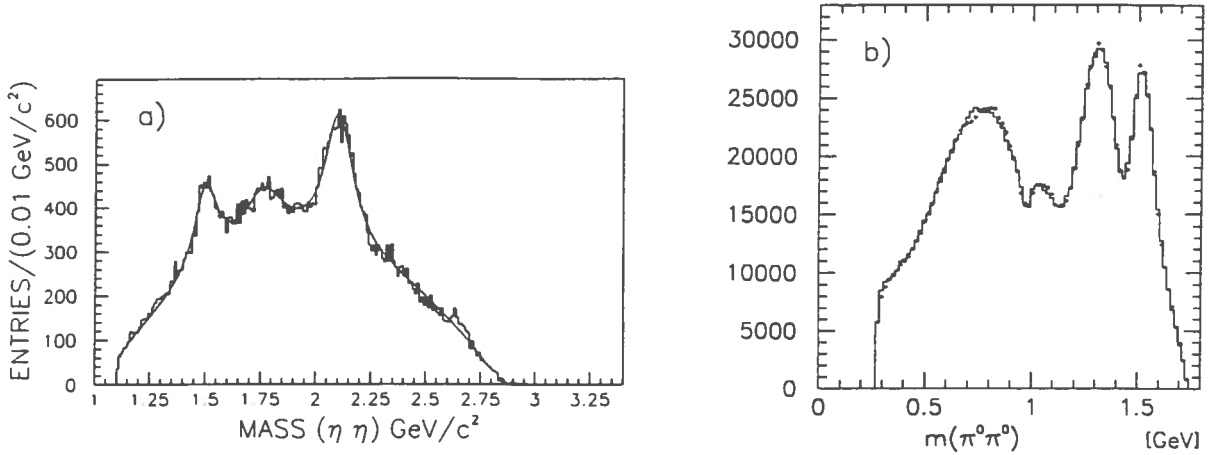


Figure 8: a) $\eta\eta$ effective mass from the reaction $\bar{p}p \rightarrow \pi^0(\eta\eta)$ at 3.0 GeV c.m. energy (E760); b) $\pi^0\pi^0$ mass distribution from the reaction $\bar{p}p \rightarrow 3\pi^0$ at rest (Crystal Barrel).

This change reflects in a completely different scenario for the interpretation of this state: from a possible nucleon-antinucleon bound state to a possible gluonium state. In this latter hypothesis one may wonder: why this state has not been observed before in J/ψ decays or central production? A partial solution could come from a reanalysis of the $J/\psi \rightarrow \gamma 4\pi$ data. The 4π mass spectrum is shown in fig. 9 and the arrow indicate an enhancement consistent in mass and width with $f_0(1520)$.

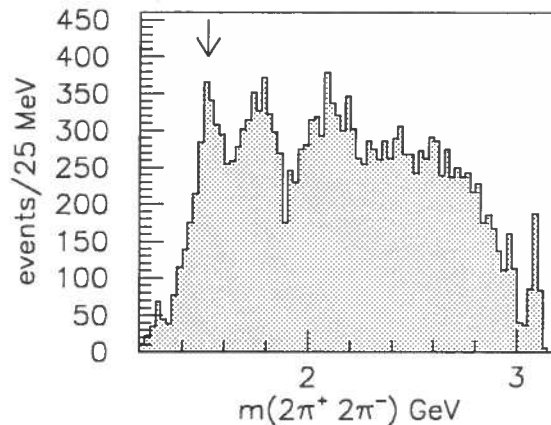


Figure 9: 4π mass spectrum from $J/\psi \rightarrow \gamma 4\pi$ (DM2). The arrow indicates the mass of the $f_0(1520)$.

A new spin analysis has been performed and the spin parity of this state has moved from $J^P = 0^-$ to $J^P = 0^+$, mostly due again to a change in the parametrization of the $\pi\pi$ S-wave [15]. However, this does not explain why this state has not been observed in the $J/\psi \rightarrow \gamma(\pi\pi)$ final state. In conclusion, we could open here a new page in physics but still

other elements of the scalars puzzle have to fit all together.

2.6 $\theta(1710)$

This state has been discovered in radiative J/ψ decay to $K\bar{K}$ and $\pi\pi$ (see fig. 10a).

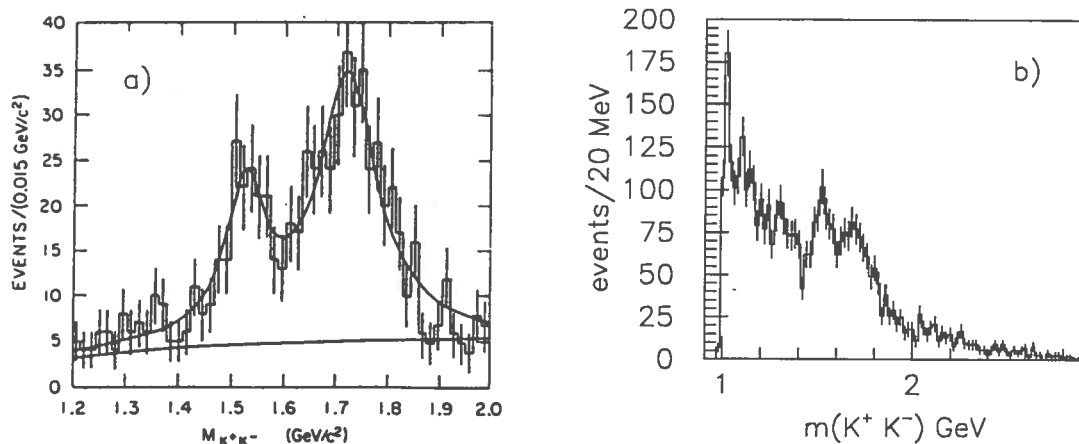


Figure 10: a) K^+K^- mass spectrum from $J/\psi \rightarrow \gamma K^+K^-$ (MarkIII); b) K^+K^- mass spectrum from $pp \rightarrow p_f(K^+K^-)p_s$ (Ω -WA 76).

Its spin was measured to be 2 in the assumption that only one state was present in $\theta(1710)$ mass region. Further evidence for this state came from central production (fig. 10b) where the spin was found to be consistent with 2.

However, the MarkIII group repeated the spin analysis of the $\theta(1710)$ by using the method of moments and allowing the presence of interfering S and D waves [16]. The results changed quite drastically: the D-wave was found to be small while the S-wave in the $\theta(1710)$ region was dominant. In conclusion, $\theta(1710)$ became a scalar resonance. How is this possible?

The key is again in the low statistics and in the poor geometrical acceptance of the apparatus in important kinematical regions. Where the two different spin configurations could differ significantly, the acceptance of the apparatus is small. In the end, in part due to the limited statistics, the two spin hypotheses cannot be discriminated and which leads to a change of the results according to the method of analysis.

The spin analysis of $\theta(1710)$ from central production, on the other hand, is affected by a different problem. Here the Gottfried-Jackson frame used to calculate the angular distributions is poorly defined and this makes a proper Partial Wave Analysis difficult. In addition, the central production process is contaminated by the tails of diffractive contributions which produce asymmetries in the angular distributions.

Further information comes from the study of J/ψ decays at BES (Beijing) [17]. With a statistics similar to those obtained at SLAC they obtain indications for spin 2 for $\theta(1710)$

in the study of $\omega K\bar{K}$, $\gamma\pi^0\pi^0$ and γK^+K^- final states. A spin 0 contribution is also found to be present in the high mass side of the $K\bar{K}$ structure.

Are there two states at $\theta(1710)$? At moment it is probably safer to move back $\theta(1710)$ to the spin 2 sector.

2.7 Summary of the Scalar Mesons.

The situation can be largely clarified by removing critical states below a given threshold. A possible scheme includes in the established scalar mesons a possible nonet formed with $a_0(980)$, $K_0^*(1430)$, $f_0(975)$ and $f_0(1400)$. The new state, $AX/f_0(1520)$, remains as an extra state whose origin is still unclear but is a good candidate for being the scalar glueball. However, we are still left with considerable problems of this multiplet. The mass of the $s\bar{s}$ member ($f_0(975)$) is, in fact, unexplicably lower than the mass of the $u\bar{u} + d\bar{d}$ member ($f_0(1400)$). In addition two states $a_0(980)$ and $f_0(975)$ are too narrow and placed just at the $K\bar{K}$ threshold. There is still very much to understand here.

3 TENSOR MESONS

The status of $J^{PC} = 2^{++}$ mesons is summarized in fig. 11 where the actual meson candidates are compared with the expectations from the quark model: one can see a rather good agreement.

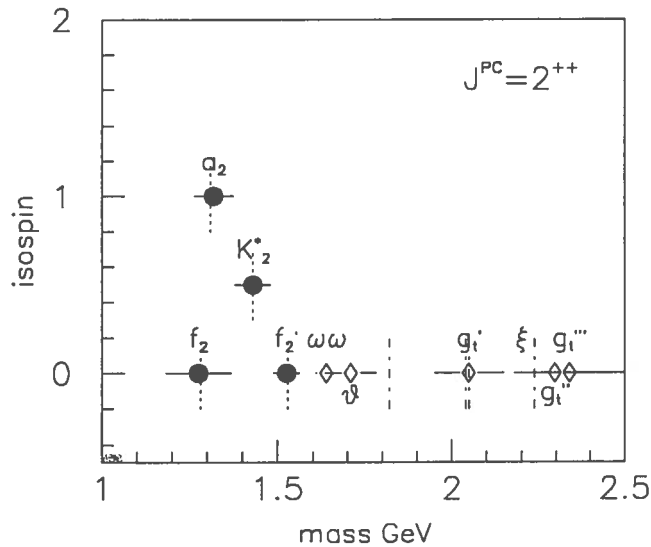


Figure 11: *Status of the tensor mesons. Symbols represent the experimental masses, horizontal bars their widths. Vertical bars represent the expectations from the GI model.*

However we can also notice a relative abundance of extra states. In addition, due to the discussion outlined in the previous chapter, $\theta(1710)$ has also been listed in this sector. Let us analyze the extra states closer.

3.1 $X(1640)$

This state has been observed in π^- interactions and in the $\omega\omega$ decay mode. It was first observed by GAMS experiment [18] and then confirmed by VES at IHEP [19] (see fig. 12). Indications for this state are also present in $\bar{p}p$ annihilations and possibly in central production.

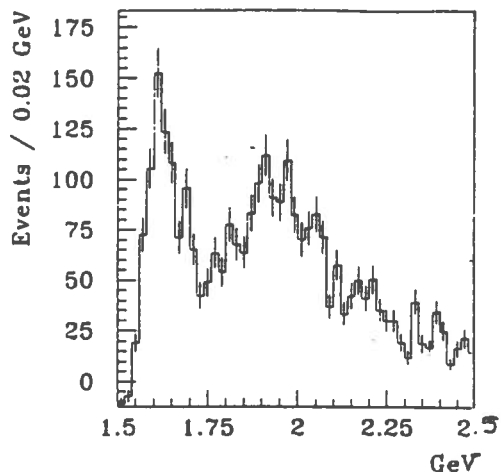


Figure 12: $\omega\omega$ mass distribution from $\pi^- p \rightarrow \omega\omega n$ (VES/IHEP).

3.2 The g_T states

The observation of a large cross section for the OZI suppressed reaction $\pi^- p \rightarrow \phi\phi n$ at 22 GeV/c at BNL has been interpreted by the authors as due to the production of intermediate glueball resonances [20]. The argument, however, has been controversial for long time. In particular, according to H. Lipkin [21], an OZI forbidden process can always proceed as a two step process in which each of the individual steps is allowed. On the experimental side, a PWA of the $\phi\phi$ mass spectrum shown in fig. 13 gives evidence for three wide states, named g_T 's for tensor glueballs.

Further information on the $\phi\phi$ final states comes from inclusive interactions on Beryllium from 85 GeV/c π^- at the CERN Ω spectrometer [22]. On the basis of a fit to a background subtracted $\phi\phi$ mass spectrum they derive the presence of two wide structures. Masses and widths of the states found in the two experiments are compared in fig. 14, but it is not clear how large the agreement is. $\phi\phi$ production from other experiments has been attempted, but has not been conclusive due to the limited statistics.

In conclusion, the evidence for resonances or glueballs in the $\phi\phi$ channel needs to be confirmed.

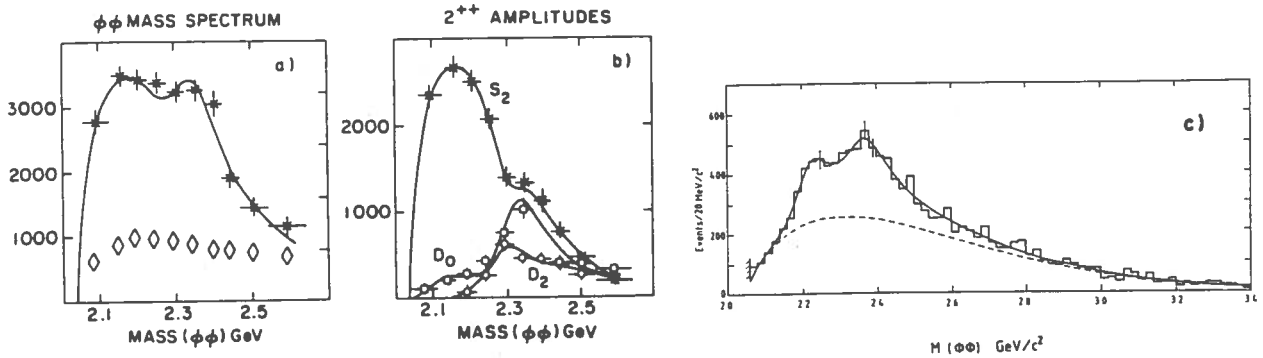


Figure 13: a) $\phi\phi$ mass distribution from $\pi^-p \rightarrow \phi\phi n$ (BNL) and b) results from the PWA; c) Background subtracted $\phi\phi$ mass spectrum from Ω -WA67.

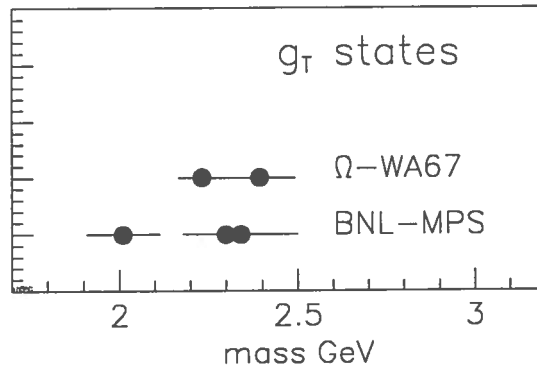


Figure 14: Comparison between mass and widths of the states found to decay to $\phi\phi$.

3.3 Summary on the tensor mesons

By using the well established 2^{++} mesons an ideally mixed nonet is obtained with $a_2(1320)$, $K_2^*(1430)$, $f_2(1270)$ and $f_2'(1520)$ mesons. We are then left with two extra states, $f_2(1640)$ and $\theta(1710)$. The latter, if confirmed as being a spin 2 resonance, presents very peculiar characteristics which could point to an exotic nature of this state. It is, in fact, only observed in supposed "gluon rich" reactions and not in peripheral reactions or $\gamma\gamma$ collisions.

4 PSEUDOSCALAR MESONS

4.1 $\iota/\eta(1440)$

The initiation of gluonium spectroscopy was generated by the large and unexpected $\iota/\eta(1440)$ signal observed in radiative J/ψ decay in the $K\bar{K}\pi$ final state (see 15a)

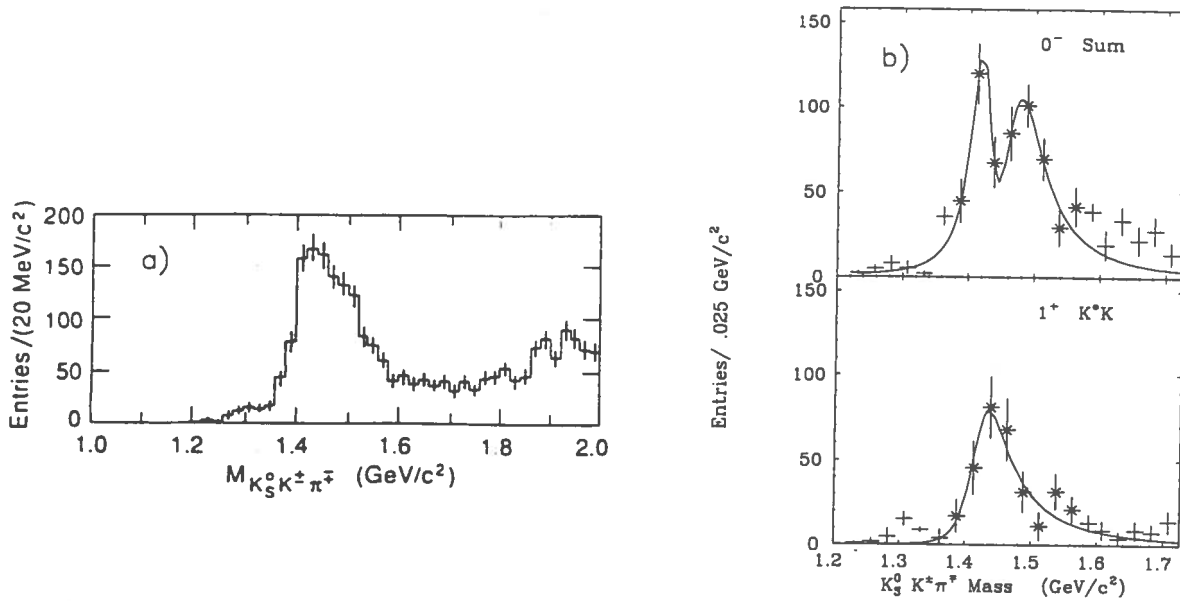


Figure 15: a) $K\bar{K}\pi$ mass spectrum and b) Spin analysis of the $K\bar{K}\pi$ mass spectrum from $J/\psi \rightarrow \gamma K\bar{K}\pi$ (MarkIII).

The spin-parity analysis of this state was performed by different experiments all converging to a pseudoscalar nature of this resonance. The observation of $\iota/\eta(1440)$ in a gluon rich channel and not in $\gamma\gamma$ collisions readily pointed to a possible gluonium nature of the state. However, some piece of the puzzle did not fit well. In particular, the presence of an axial meson ($f_1(1420)$) in the same mass range, observed in hadronic J/ψ decays and not in radiative decays, was not understood. It was also not clear how the radiative J/ψ decay to $\eta\pi\pi$ was consistent with an $a_0(980)\pi$ decay. Finally, the $\iota/\eta(1440)$ lineshape was distorted and not easily described by only one resonance.

It is possible that all these problems have been solved by a more recent spin-parity analysis of the $K\bar{K}\pi$ and $\eta\pi\pi$ systems performed by two different experiments [23, 24]. The results show that in the 1.4 GeV region not one but *three* different states exist: two pseudoscalars and one axial. However, the two experiments, while agreeing with the number of states, find different masses for these objects. The results from the MarkIII analysis are shown in fig. 15b).

With this in mind the experimental situation of the pseudoscalar mesons is compared with the expectations from the quark model in fig. 16.

In the GI model, however, there are two possible schemes for the pseudoscalar mesons. The one shown in fig. 16, is labelled P1, differing from scheme P2 for what concerns the masses of the radial excitations. This latter scheme has been mainly proposed in order to explain the existence of a pseudoscalar meson: $\eta(1295)$. How solid is this state?

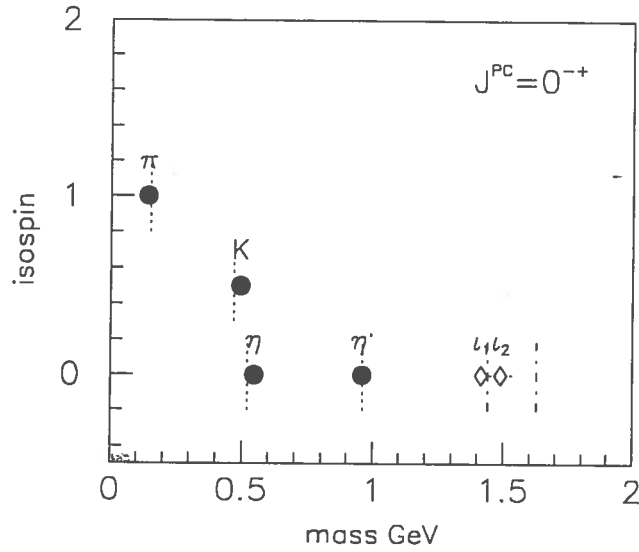


Figure 16: *Status of the pseudoscalar mesons. Symbols represent the experimental masses, horizontal bars their widths. Vertical bars represent the expectations from the GI model.*

4.2 $\eta(1295)$

This resonance was firstly evidenced by a PWA of the $\eta\pi\pi$ system in π^- interactions at Argonne [25]. It was then confirmed by two experiments at KEK [26, 27]. All the experiments made use of the same PWA program. The results from the KEK experiment are shown in fig. 17.

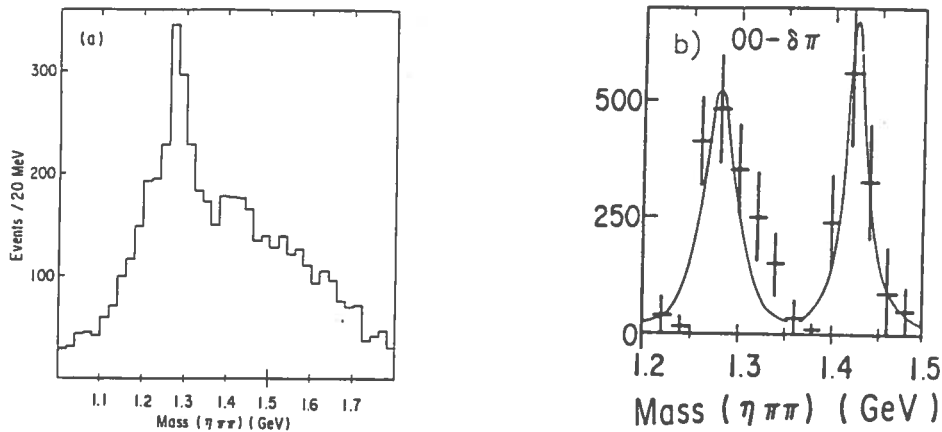


Figure 17: *The evidence for $\eta(1295)$. a) $\eta\pi^+\pi^-$ mass spectrum from the reaction $\pi^-p \rightarrow \eta\pi^+\pi^-n$; b) pseudoscalar contribution. The data are from KEK.*

One can notice that the mass spectrum is dominated, in the 1290 MeV mass region, by a narrow peak due to the presence of the $f_1(1285)$ meson. However, the PWA sort out another pseudoscalar resonance, placed just below $f_1(1285)$: $\eta(1295)$. One can also notice the large amount of background present in this final state.

If this resonance exists, it should also be seen in other experiments and processes. However, this is not the case. Very clean $\eta\pi\pi$ mass spectra have been produced in $\gamma\gamma$ collisions, central production and J/ψ decays. $\eta(1295)$ was not observed even when the production of pseudoscalars was clearly favoured. In conclusion the status of this state is somewhat critical and requires confirmation.

4.3 Summary on pseudoscalar mesons

Unfortunately, as can be seen in fig. 16, the $\iota/\eta(1440)$ is just in the place where radial excitations are expected. This does not help this state for being a good glueball candidate. In addition, the number of pseudoscalars really present in the ι structure needs confirmation. New data from J/ψ decays and $\bar{p}p$ at rest and in flight may help to solve the $\iota/\eta(1440)$ puzzle.

5 AXIAL MESONS

The status of the axial mesons is summarized in fig. 18.

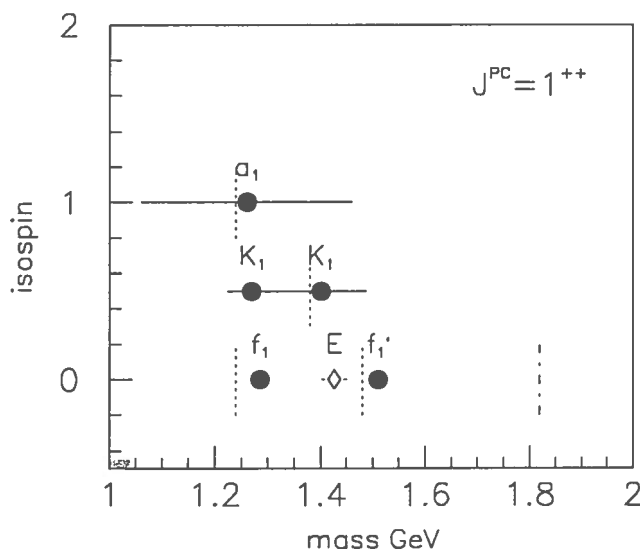


Figure 18: *Status of the axial mesons. Symbols represent the experimental masses, horizontal bars their widths. Vertical bars represent the expectations from the GI model. The physical state K_{1A} is a nearly 45° mixed state of $K_1(1270)$ and $K_1(1400)$*

We notice a fair agreement with the ideally mixed nonet expected from the quark-model. We also notice the presence, in the same multiplet, of very wide ($a_1(1270)$) and very narrow states (like $f_1(1285)$). Two states are competing for being the $I=0$ $s\bar{s}$ member of this nonet: $E/f_1(1420)$ and $f_1(1510)$.

5.1 $E/f_1(1420)$

The best observation of this meson was made in central production at the CERN- Ω spectrometer [28] (see fig. 19a).

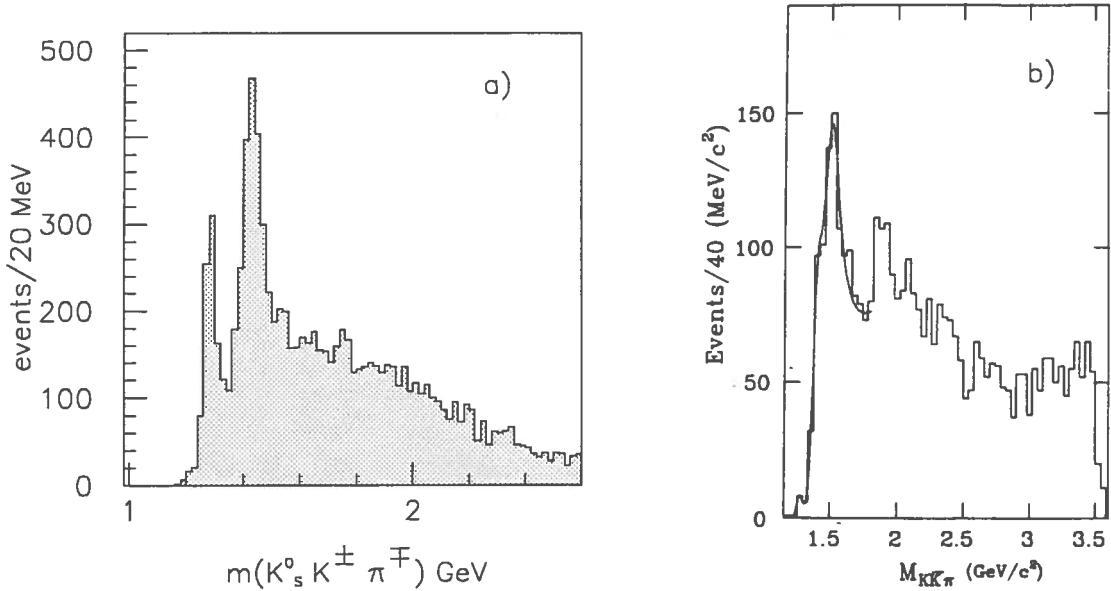


Figure 19: a) The observation of $E/f_1(1420) \rightarrow K\bar{K}\pi$ in the reaction $pp \rightarrow p_f(K\bar{K}\pi)p_s$ (Ω -WA76). b) The evidence for $f_1(1510)$ in the reaction $K^-p \rightarrow K\bar{K}\pi\Lambda$ (LASS).

In addition, several evidences of $f_1(1420)$ have been reported in J/ψ decays, $\gamma\gamma$ collisions and possibly in π induced reactions. In the latter case, however, two experiments report different results. In one case [29] the peak observed in the mass spectrum is attributed to the axial meson, in the other case the peak is attributed to a complex mixture of states dominated by a pseudoscalar [30].

The $E/f_1(1420)$ meson presents peculiar characteristics which make it an interesting resonance. It has only been observed to decay to $K^*\bar{K}$ and has a mass very close this threshold, a fact which has prompted some authors to suggest a molecular interpretation for this state. If it is confirmed (see later) as being an extra state, then it does not fit well into the quark model. It cannot be a glueball due to its large $\gamma\gamma$ width, therefore it has been proposed for being a hybrid $(u\bar{u} + d\bar{d})g$ meson.

5.2 $f_1(1515)$

The evidence for this meson comes from the study of the $K\bar{K}\pi$ system in K^- interactions. Two experiments report the evidence for an axial meson in the 1.51 GeV region but with different results and different analysis methods (see fig. 19b)). The key point is an asymmetry in the Dalitz plot of the $K\bar{K}\pi$ system which describes the decay of this state.

In one case [31] this asymmetry is interpreted as due to the production of incoherent K^* production, in the second case [32] as due to the interference between two resonances: 1^{++} ($f_1(1515)$) and 1^{+-} ($h_1(1380)$). Both experiments suffer from a rather low statistics. Possible evidence for this state (but with no spin determination) comes from π^- interactions. Due to the interest in this sector, it would be nice to have an independent, high quality, observation of this resonance.

6 EXOTICS?

The observation of states having quantum numbers forbidden for a $q\bar{q}$ resonance (like 0^{--} , 0^{+-} , 1^{+-} , 2^{+-} , etc) would greatly enhance gluonium spectroscopy. Therefore, there was much interest in the evidence reported by the GAMS experiment for an exotic 1^{+-} resonance $\rho(1405) \rightarrow \eta\pi^0$ produced in π^-p interactions [33].

However (see sect. 2) the $\eta\pi^0$ mass spectrum is dominated by the presence of a large $a_2(1320)$. The key evidence for this state is a forward-backward asymmetry in $\cos\theta_{GJ}$ which can only be explained by an interference of $a_2(1320)$ with an odd spin wave. Whether this wave is resonating is not well established. The GAMS analysis suffers from ambiguities in the partial waves decomposition. Further information is reported at KEK [34] but with a 1^{+-} wave having somewhat different parameters.

A large statistics experiment analyzing the $\eta\pi^-$ final state in π^- interactions (VES at Serpukhov) [35], while reporting a broad 1^{+-} wave, does not confirm the existence of the GAMS state. Similar conclusions arise from $\bar{p}p$ annihilations. In conclusion, the existence of this kind of exotics still needs to be proven.

Another possible intrinsically exotic state comes from the Lepton-F experiment at Serpukhov which reported a $J^{PC} = 1^{--}$ $C/\rho(1450) \rightarrow \phi\pi^0$ in π^-p interactions at 32 GeV/c [36]. However, here again, the evidence for this state is not straightforward since the $K^+K^-\pi^0$ mass spectrum is dominated by an unresolved $f_1(1420)/\eta(1420)$ structure. This state has been searched for but not confirmed by any other experiment.

7 CONCLUSIONS

After 15 years of searching for a gluonium spectroscopy where are we? Several new states have been discovered and several J^{PC} multiplets have been completed. There remain, however, a consistent number of resonances which do not fit the quark model. Some of these states require confirmation, but some of them are very promising and could point to the existence of states having valence glue. In particular, $\iota/\eta(1440)$, $E/f_1(1420)$, $S^*/f_0(975)$, $AX/f_0(1520)$ and $\theta(1710)$ are solid candidates for being something interesting. What is needed is confirmation of these states and understanding through high statistics and high quality experiments.

References

- [1] M. Doser and A. Palano, BARI-TH/172-94, April 1994. Proceedings of the 3rd Workshop on a τ -charm factory, Marbella, Spain, June 1-6 1993.
- [2] L. Kopke and N. Wermes, Phys. Rep. 174 (1989) 67.
- [3] A. Palano, Proceedings of the IX Workshop on photon-photon collisions, San Diego, 22-26 March 1992, World Scientific, 308.
- [4] C. Amsler, UZH-PH-100/93, Czechoslovak Journal of Physics.
- [5] H. Kolanoski, Proceedings of the IX Workshop on photon-photon collisions, San Diego, 22-26 March 1992, World Scientific, 3.
- [6] S. Godfrey and N. Isgur, Phys. Rev. D32 (1985) 189.
- [7] A. Palano, private communication, unpublished.
- [8] D. Aston et al., Phys. Lett. 215B (1988) 199.
- [9] M. Boutemer and M. Poulet, Proceedings of Hadron 89, Ajaccio, France, Editions Frontieres, 119.
- [10] F. Antinori et al, Phys. Lett. B324 (1994) 509.
- [11] D. Morgan, RAL-93-078, Proceedings of Hadron 93, Como, Italy, World Scientific.
- [12] D. Alde et al., Nucl. Phys. B269 (1986) 485.
- [13] V.V. Anisovich, et al., Phys. Lett. B323 (1994) 233.
- [14] T. Armstrong et al., Phys. Lett. B307 (1993) 399.
- [15] D. Bugg, private communication.
- [16] L.P. Chen et al., Nucl. Phys. B (Proc. Suppl.) 21 (1991) 80.
- [17] Z. Zhipeng, XVI Intern. Symp. on Lepton-Photon Interactions, Cornell, 1993.
- [18] Alde et al, Phys. Lett. B205 (1988) 451.
- [19] G.M. Beladidze et al., Z. Phys. C54 (1992) 367.
- [20] A. Etkin et al., Phys. Lett. B201 (1988) 568.
- [21] H. Lipkin, Phys. Lett. B124 (1983) 509.
- [22] P. Booth et al., Nucl. Phys. B273 (1986) 677.
- [23] Z. Bai et al., Phys. Rev. Lett. 65 (1990) 2507.
- [24] J.E. Augustin et al., Phys. Rev D46 (1992) 1951.
- [25] N. Stanton et al., Phys. Rev. Lett. 42 (1979) 346.
- [26] A. Ando et al., Phys. Rev. Lett. 57 (1986) 1296.
- [27] S. Fukui et al., Phys. Lett. B267 (1991) 293.
- [28] T.A. Armstrong et al. Z. Phys. C52 (1991) 389.
- [29] C. Dionisi et al., Nucl. Phys. B169 (1980) 1.
- [30] A. Birman et al., Phys. Rev. Lett. 61 (1988) 1557.
- [31] Ph. Gavillet et al., Z. Phys. C16 (1982) 119.
- [32] D. Aston et al., Phys. Lett. B201 (1988) 573.
- [33] D. Alde et al., Phys. Lett. B205 (1988) 397.
- [34] H. Aoyagi et al., Phys Lett, B314 (1993) 246.
- [35] G.M. Beladidze et al., Phys. Lett. B313 (1993) 276.
- [36] S.I. Bityukov et al., Phys. Lett. B188 (1987) 383.