Glueballs, Hybrids and the Standard Model: Hadron '97 Summary (Experiment)

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HADRON '97 covered a wide spectrum of particle physics, from high-Q^2 events in e^+-proton collisions at DESY to the recent discovery of 1^{-+} exotic mesons. This paper reviews progress reported at the conference, in particular the status of glueballs and hybrids. Personal views and interpretations are offfered, sometimes at variance with accepted views.

1 Introduction

The role of gluons in hadron spectroscopy is the continuing theme of the HADRON conferences. Also after HADRON '97 this role is still controversial. Many speakers expressed their believe that evidence for the lowest-mass glueball is overwhelming, that it is a scalar state and that it mixes with the isoscalar 1^3P_0 mesons. But there is no agreement on a number of questions which are very important for a real understanding of how a primordial glueball enters the world of quarkonia: Is the Crystal-Barrel $f_0(1500)$ the glueball with some $\bar{q}q$ component mixed in or does the $f_0(1710)$, the old $\Theta(1690)$ with ambiguous spin assignment, play this eminent role? Are we missing a $s\bar{s}$ scalar meson and why did LASS not find it? Can we resolve the discrepant results on radiative J/ψ decays? Is the evidence for the $f_0(1370)$ convincing enough to provide a cornerstone in our understanding of glueballs?

Problems of mixing with ordinary mesons do not occur for hybrids carrying exotic quantum numbers. Mesons of $\bar{q}q$ structure with orbital angular momentum l and total spin s must have parity $P = (-1)^{l+1}$ and C-parity $C = (-1)^{l+s}$. Mesons with quantum numbers $J^{PC} = 1^{-+}$ can thus not be oridinary $\bar{q}q$ system; they are *exotic*. We shall discuss evidence for the $J^{PC} = 1^{-+}$ wave as evidence for hybrids, for $\bar{q}qg$ structure. Of course, a interpretation as $\bar{q}q\bar{q}q$ state is not excluded.

HADRON '97 was not a conference on glue. We listened to an update of the exciting news on the possibilty that the frontiers of the Standard Model may have been reached or surpassed in high Q^2 events at HERA; top- and bottom-quark physics was reviewed as well as the status of our understanding of fragmentation. Searches for other types of exotic matter, the H dibaryon, pentaquarks, or high-mass baryons with hidden strangeness were discussed. The conference also offered the room for presenting new results on conventional hadron spectroscopy where strong evidence emerged that we can use $^3P_0$-model calculations to decide on the nature of specific states. It is of course impossible to review in a single paper the full scope of an exciting conference, in particular one with five parallel sessions. But I tried at least to mention one highlight of each plenary talk. From the parallel sessions I took the priviledge to discuss only those results which happen to fit into the mainstream of the review.

Finally I should emphasize strongly that I appreciated very much the scientific atmosphere of the conference under the leadership of Suh Urk Chung and with the helpful organisation by Hans Willutzki and his team. Many discussions with numerous people helped me to understand better the importance of results and their relations to other fields. Of course, I am responsible for any misunderstanding or errors in the final text. I would like to use this opportunity to thank all those who helped to organise this exciting conference and who made it to the success it undoubtedly was.

2 THE STANDARD MODEL AND BEYOND

The Standard Model of six quarks and leptons grouped pairwise into three families and interacting via electroweak and interquark forces has proven to be a remarkable success. Until now all claims for inconsistency have been resolved. The Standard Model can, on the other hand, not provide a complete picture of nature. There are too many parameters to be determined from experiments; in particular the mechanism of mass generation remains unexplained. So any experiment exploring a new energy regime has the chance to challenge the Standard Model. But also precison tests may reveal small inconsistencies between experiment and Standard-Model predictions, and may thus point towards the advent of new physics.

The unexpected excess of events of backscattered positrons in e^+p scattering at HERA reported early this year [2, 3] have stimulated speculations on the nature of this phenomenon. The hypothesis that leptoquarks exist, particles with both quark and lepton numbers, is not the only possible interpretation of the excess but certainly a very exciting one. I will discuss the DESY results under this aspect.

Leptoquarks

- Excess of events at very high Q^2 at DESY

An extraordinary type of events taken at DESY with the H1 and the Zeus detectors was shown by Schultz-Coulon [1] and by Derrick [1] in which 27.5 GeV positrons entered the detector and underwent a collision with a 820 GeV proton. The collision occurred at an energy in the cms system of $\sqrt{s} = 300$GeV, the largest value accessible today in accelerator experiments. In an event shown at the conference the positron was reflected in backward direction after a momentum transfer of $\sim$ 160 GeV. The hit quark hadronised and gave rise to an energetic jet. The positron-jet invariant mass was 200 GeV. Such events are not excluded by Standard Model calculations. Surprising is the rate with which these events occurred. The distribution of events for positrons scattered off protons at HERA energies with high Q^2 as a function of the positron-jet invariant mass M ($\sqrt{xs}$) and of the fractional change in positron energy (y) shows an excess in the region $Q^2 \geq 15000\mathrm{GeV}^2$. The excess was seen in both experiments even though there were statistically significant differences between the two experiments. New data taken this year are now compatible with QCD predictions but in the sum of all data the excess is still significant.

The excess of high-Q^2 events is concentrated at large ($e^+ - jet$) invariant masses. This fact may hint at the exciting possibility that leptoquarks with a mass of about 200 GeV could be responsible for the new phenomenon. Leptoquarks are different from all known particles, they carry both lepton number and color. Their existence would provide the proof for a link between quark and lepton families expected from triangle anomalies which cancel only when quarks and leptons are combined into generations by higher symmetries.

- Search for leptoquarks at Fermilab

If leptoquarks exist they should be produced pairwise ($LQ\overline{LQ}$) in antiproton-proton collisions. Bertram [1] reported on searches for leptoquarks at Tevatron. If leptoquark decays are forbidden into particles not belonging to the same generation and also have no other strong decay modes, then the lightest LQ's – supposedly observed at 200 GeV – need to manisfest themselves in final states with a ($e^+ - jet$)- and ($e^- - jet$)-pair both having an invariant mass of 200 GeV. Events with such a pattern are extremely rare. This allows to set a tight lower limit on the LQ mass. Combining the results obtained by the D0 and the CDF collaborations, a lower limit of 220 GeV was given excluding a straightforward LQ interpretation of the DESY result. Leptoquarks with different decay patterns are not excluded by the Fermilab result. Obviously, we are expecting anxiously new data sets from DESY.

- Evidence for the decay $\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}$

Rare Kaon decays allow to set stringent lower upper on new physics, in particular also on the mass of leptoquarks. It was therefore exciting to hear that one event of type $\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}$ was unambiguously identified at BNL [4]. However, the group emphasised that the event is fully consistent with Standard Model predictions.

Scrutinizing the Standard Model

- The top quark mass

The top quark - just discovered - is pinned down in precision experiments.

Thomas [1] reported on production of $t\bar{t}$ pairs in various final states:

$$t\bar{t} \rightarrow\ W + \text{jets} + X \qquad t\bar{t} \rightarrow\ W + b + \text{jets} + X \qquad t\bar{t} \rightarrow\ l^+ l^- + \text{jets} + X$$
$$t\bar{t} \rightarrow\ l^+ + \tau\ + \text{jets} + X \qquad t\bar{t} \rightarrow\ \text{jets} + X$$

Top-quark mass and cross sections were determined, to a remarkable precision. The mean value for the top quark mass is now given

$$M_{top} = (175.6 \pm\ 5.5)\ GeV/c^2 \tag{1}$$

i.e. with a precision of $\sim 3\%$. The experimental cross section agrees very well with QCD predictions; there is no inconsistency with the Standard Model in top production or decay.

- Searches for new particles

Physicists are inventive: models and proposals to search for phenomena beyond the Standard Model are numerous. One or more Higgs particles are expected, additional left- or right-handed charged or neutral vector bosons might exist, or excited quarks, techni-rhos, $E6$ diquarks, families of supersymmetric particles, among others. Pan and Bertram [1] gave updates on upper limits for their production at LEPII and at Fermilab, respectively. The search for new phenomena is important – it would be desastruous to miss new physics in the data by not looking for it – the repetition of selection chains and upper limits sometimes less exciting.

- Fragmentation

A thorough understanding of parton fragmentation is mandatory for many aspects in high-energy physics since processes on the parton level are observed only indirectly through hadronic final states. Experimental studies of fragmentations are therefore crucial. Lafferty [1] reported on the impressive agreement between the multiplicities observed in Z^0 decays and those calculated in different fragmentation models. We will come back to this issue in the discussion on properties of the $f_0(980)$. For polarised e^+ and e^- beams, the production of quarks and antiquarks is asymmetric with respect to the electron direction. Hence the fragmentation of quarks and antiquarks can be studied separately as Aston [1] demonstrated in his talk. It is thus possible to tag quark jets and antiquark jets, gluon jets and jets developing from the production of light, charmed or bottom quarks. He also presented evidence for flavor independence of the strong coupling constant α_s.

- b-quark physics

B decays

The Stanford Linear Collider requires extremely precise focussing of e^+ and e^- beams; the radial spot size of the interaction region is $\sim 7\mu m$. Jointly with high-precison vertex detectors with a spatial resolution of $\sim 5\mu m$, lifetimes of charged and neutral B-mesons could be determined and compared accurately. Aston [1] reported new life-time results. World averages on the life times were given as

$$\tau(B^-) = (1.67 \pm 0.04)\ \mathrm{ps} \quad \tau(B^0) = (1.57 \pm 0.04)\ \mathrm{ps} \quad \frac{\tau(B^-)}{\tau(B^0)} = 1.07 \pm\ 0.04$$

The mean life time is substantially larger than a few years ago and the ratio different from unity, indicating a breakdown of the spectator picture for the weak decay.

The study of exclusive B decays and the measurement of their frequencies is important because of the forthcoming CP violation searches in the b-quark sector. Gronberg [1] gave an update on recent measurements of B-meson decay rates, and several new reactions were found. Among these were the first B decay rate into 2 mesons with first-generation quarks only (into $\pi\omega$).

b-quark production at Fermilab

Cross sections for $\mathrm{B}^{\pm}$-meson production measured at Fermilab at $\sqrt{s}$ = 1.8TeV are systematically larger by about a factor 2 compared to QCD predictions as reported by Thomas [1]. The B-mesons are fully recontructed via their decays into J/ψ and a K or K^* and their secondary vertex was identified. The discrepancy persisted at lower energies ($\sqrt{s} = 0.63$TeV). The findings were not commented at the conference; it remained unclear if the results challenge the Standard Model or if other explanations could be envisaged.

- Charmonium and bottonium spectroscopy

BES results

The discovery of the J/ψ states had marked a breakthrough in our understanding of the basic constituents in particle physics. Still today it provides a laboratory for fundamental research. At Hadron '97 new data were presented from BES by Shen [1] on decay rates of the χ_c states including measurements of yet unseen channels. Reactions which were observed before are determined with branching ratios which are mostly lower by a factor 2 or 3 than previously reported values. The large discrepancy is worrysome since it may indicate problems in reconstruction efficiency. Data on radiative J/ψ decays will be commented upon in a later section.

Results from Fermilab E

The E835 experiment at Fermilab and its precessor E760 have provided a wealth of very precise data on the charmonium states. The power of forming $c\bar{c}$ states in $\bar{\mathrm{p}}\mathrm{p}$ annihilation was demonstrated by Zioulas [1] by comparing production of the η_c in $\bar{\mathrm{p}}\mathrm{p}$ formation and subsequent decay into $\gamma\gamma$ with data on 2 photon fusion in the reaction $e^+e^-\to e^+e^-\mathrm{K}^0_s\mathrm{K}\pi$. The 2-photon width can be determined in both ways; the results are $\Gamma\gamma\gamma = (3.7^{+1.5}_{-1.3})$keV from E835 and $\Gamma\gamma\gamma = (5.7 \pm 2.4)$keV from Cornell data.

- Chiral perturbation theory

Up and down quarks are nearly massless and thus obey chiral invariance. This aspect of QCD leads to non-trivial predictions in the low-energy domain. To consider tests of chiral perturbation theory (ChPT) as tests of QCD is certainly benevolent but not wrong. Thus I will discuss under this heading the tests of ChPT presented at Hadron '97. These were related to the decay dynamics of isoscalar pseudoscalar mesons. Shibata [1] pointed out that the decays $\eta \to 3\pi$ and $\eta' \to \pi\pi\eta$ follow approximately phase space distributions with corrections due to ChPT while high mass states like ψ' and $Y(2S)$ decay into $\pi\pi$ plus ground state with large deviations from phase space in the $\pi\pi$ invariant mass spectrum.

Decay dynamics of η mesons

Doser [1] presented η decay Dalitz plots for $\eta \to \pi^+\pi^-\pi^0$ and into $3\pi^0$. Both Dalitz plots show slight deviations from uniformity which are parameterized as functions of the normalised π^0 kinetic energy (for $\pi^+\pi^-\pi^0$) or distance from the Dalitz plot center (for $3\pi^0$). While the former is consistent with ChPT calculations, the latter distribution shows significant deviations from ChPT results.

Box anomaly in η' decays

The decay $\eta' \to \pi^+\pi^-\gamma$ proceeds dominantly via radiative production of ρ-mesons but the so-called box diagram permits decay into 2π S-wave. This decay is predicted within current algebra and chiral dynamics. So far, a total of 8000 events was recorded in 9 different experiments, a statistics which is now obtained in the Crystal Barrel experiment and $\bar{p}p$ annihilation at rest. It should be noted that the result is model dependent. Crystal Barrel data are consistent with QCD and fractional quark charges, pseudoscalar nonet symmetry, and the known pseudoscalar mixing angle. It requires, however, a modification of the ρ line-shape from vector meson dominance. This result has to be contrasted to that of L3 (presented by Lafferty [1]) studying 2-photon fusion into $\pi^+\pi^-\gamma$. Based on about 2500 η' events, L3 finds a perfect fit for no box anomaly and rejects the Crystal Barrel result.

Coulomb production of $\pi\eta$

The box anomaly should also be present in $\eta \to \pi^+\pi^-\gamma$ decays. Zaitsev [1] presented an alternative approach: he showed positive evidence for Coulomb production of $\eta\pi^-$ in pion scattering in a Coulomb field. The data required a large chiral anomaly.

Rare Φ decays

The Φ factory at Frascati will provide very precise data on rare decays of Φ mesons and, in particular, permit a study of CP violation in the strange quark sector. However, also the VEPP-2M at Novosibirsk has increased its luminosity and allows a first look at rare reactions. Serednyakov [1] presented the status of the accelerator complex and recent results obtained with the Spherical Neutral

Detector (SND) and the CMD-2 detector. A large number of reactions was studied, among these radiative Φ decays into $\pi^0\pi^0$ and $\pi^0\eta$ which have never been seen before. These will be discussed later. The reaction with the smallest rate, $\Phi\rightarrow\pi^0 e^+e^-$ having a branching ratio of $(1.1\pm0.8)\cdot10^{-5}$ demonstrates the sensitivity which has been achieved.

3 INTERLUDE: LONG-LIVED EXOTICS

H-Dibaryons in Heavy Ion collisons ?

The H-dibaryon, a six-quark state with 3 up, 3 down and 3 strange quarks, has attracted wide interest since the conjecture of Jaffe [5] that such a state might be bound so deeply that it is stable against decays via strong decay into $\Lambda\Lambda$. Predicted masses cluster around the 2Λ mass, hence the question of stability depends on fine details of the interactions. For weakly bound systems, a number of allowed decay modes exist (like ΛN, ΛNπ, ΣN) and the predicted life time is about 10^{-10}s. Deeply bound systems may only have NN decay modes, and the life time may exceed several days. This spread in life times makes the search so variate and challenging. Ashery [1] reported on the considerable experimental efforts to find the H but the searches remained unsuccessfull. A new chance might be given to this search in heavy-ion reactions. Longacre [1] searched for Σ^-p and Λpπ^- systems in the debris of a Si heay-ion beam of 14.6·A GeV/c momentum colliding with a Pb target. An enhancement in the Σ^-p and Λpπ^- invariant mass spectra at 2210 MeV is tentatively interpreted as evidence for H dibaryon production seen in 2 different decay modes.

Search for Pentaquarks

Systems of 4 quarks and 1 antiquark may also be stable [6] if the 4 quarks are light and the antiquark heavy, e.g. 1 $\bar{c}$, 1 s quark and 3 up and down quarks. For sufficient binding, hadronic decays into charmed particles may me forbidden. The $\bar{c}$-quark then prefers to decay weakly into an $\bar{s}$-quark plus a pion. The pentaquark can thus be searched for in its decay into proton + Φ + π. Encouraging first (low statistics) results obtained by E791 experiment were presented by Ashery [1].

Baryonic states with hidden strangeness

Landsberg [1] reported on evidence for new baryon resonances observed in diffractive production processes using a 70 GeV proton beam at IHEP impinging on a C target. The reaction products are detected with the SPHINX facility which includes a magnetic spectrometer, a RICH for particle identication and the GAMS spectrometer for the measurement of energies of γ-rays. The set up allows reliable reconstruction of ω, Φ, η and η' mesons and a clear separation of Σ and $\Sigma(1385)$ in their $\Lambda\gamma$ and $\Lambda\pi^0$ decays.

The invariant mass spectra of Σ^0K$^+$ and $\Sigma^0(1385)$K$^+$ observed in the reactions

$$p + C \rightarrow \quad \Sigma^0 K^+ \quad + C \qquad\qquad p + C \rightarrow \quad \Sigma^0(1385) K^+ \quad + C$$

exhibit resonant-like structures at 2000 and 2050 MeV, respectively. A tight cut on momentum transfer was made to guarantee coherent production off the target nucleus. Their decay into open strangeness and their narrow widths were used to argue in favor of a pentaquark interpretation ($qqqs\bar{s}$) of the resonances. Interesting new results were presented on proton induced reactions. At large momentum transfers narrow enhancements in the pη, pη' and Σ^0K$^+$ mass spectra are seen underlying the demand for higher statistics.

4 SCALAR MESON MYSTERIES

The scalar isoscalar mesons are expected to host the lowest-mass glueball, and are therefore of top interest in light-meson spectroscopy. On the other hand, in no other mesonic sector there are so many conflicting results and interpretations. In this report I shall discuss experimental data shown in the course of the conference and will try to give an interpretation which follows closely the experimental results. The status of scalar mesons was reviewed by Straßburger [1]; facts and interpretations given here are often taken from his review.

Even though our main focus is on isoscalar states, it is useful to review shortly the status of scalar isovector mesons for which new data were presented at the conference.

Isovector and strange mesons

- The strange mesons

From LASS we have precise data on Kπ scattering from which two scalar resonances have been extracted, the $K_0^*(1430)$ and the $K_0^*(1950)$. These two resonances define the mass scale for the 1^3P_0 nonet.

- The $a_0(980)$

The mass degeneracy of the $a_0(980)$ and $f_0(980)$ suggests that

(-) the $f_0(980)$ and the $a_0(980)$ should have the same structure. They should either be both $\bar{K}K$ molecules or both $\bar{q}q$ states.

(-) If they are $\bar{q}q$ state, then the scalar nonet should be ideally mixed.

Both statements do not need to be true. The molecular forces binding the $\bar{K}K$ system depend strongly on isospin: they are strongly attractive in the isoscalar system and weakly attractive for I=1. Hence it is possible that the $a_0(980)$ is a dynamical effect [10] or a $\bar{K}K$ molecule while the strongly attractive isoscalar forces lead to such a tight binding that $\bar{q}q$ interactions become predominant. Thus the $f_0(980)$ could be a $\bar{q}q$ and the $a_0(980)$ a $\bar{K}K$ state. This hypothesis could be tested by L3 at LEP by comparison of the $a_0(980)$ production characteristics with those of the $a_2(1320)$. The technique will be discussed below in connection with the $f_0(980)$.

Also if both are quarkonia, their masses are heavily influenced by the $\bar{\mathrm{K}}\mathrm{K}$ threshold. Thus their undistorted poles might be rather different, and the scalar nonet does not need to be ideally mixed. The similar masses of the $a_0(980)$ and $f_0(980)$ may be enforced by the $\bar{\mathrm{K}}\mathrm{K}$ threshold. This latter view seems most probable to me.

- The $a_0(1450)$

Two contributions were devoted to the observation of the $a_0(1450)$ in its $\bar{\mathrm{K}}\mathrm{K}$ decay mode. Doser and Heinzelmann reported on an analysis of Crystal Barrel data on $\bar{\mathrm{p}}\mathrm{p}\rightarrow\mathrm{K}^{\pm}\mathrm{K}^{0}\pi^{\mp}$ [1] while Rotondi, Vecchi and Usai [1] reported on the results obtained by the Obelix Collaboration on the same reaction. But while Crystal Barrel finds a mass and a width compatible with the result obtained in the $\pi\pi\eta$ final state (1450 MeV, 270 MeV), Obelix finds a mass of (1290 ± 10) MeV and a width of (94 ± 12) MeV. These large differences raise the question of how trustworthy the methods are to extract masses and width of resonances which are not directly seen in the data as evident structures.

Unfortunately, both isovector mesons are not ideally suited to mate with the $\mathrm{K}_0^*(1430)$. The Obelix $a_0(1300)$ would fit much better into a nonet but its mass disagrees with the Crystal Barrel findings in two different final states.

Proliferation of f_0 states

The number of proposed scalar isoscalar states in light-meson spectroscopy is very large: $f_0(750)$, $f_0(800)$, $f_0(980)$, $f_0(1000)$, $f_0(1300)$, $f_0(1370)$, $f_0(1450)$, $f_0(1500)$, $f_0(1590)$, $f_0(1710)$, $f_0(1750)$, $f_0(2100)$. We should have in mind that we expect four $\bar{\mathrm{q}}\mathrm{q}$ states in the mass range below 2.2 GeV. Their masses can be estimated from the K_0^* masses: the first strange scalar meson is found at 1430 MeV, its radial excitation at 1950 MeV. Additional states beyond the 4 expected ones could be hybrids, $\bar{\mathrm{K}}\mathrm{K}$ bound states and other molecular meson-meson states, $\bar{\mathrm{q}}\mathrm{q}\bar{\mathrm{q}}\mathrm{q}$ states and the lightest glueball. Hybrids, meson-meson bound states and $\bar{\mathrm{q}}\mathrm{q}\bar{\mathrm{q}}\mathrm{q}$ states could also have strangeness; in the strange sector there are, however, no reported resonances which cannot be accommodated in the quark model. Thus it seems unlikely that the 12 states listed above are all real.

- $\pi\pi$ scattering

Pion-pion scattering is still one of the most direct sources on scalar isoscalar interactions. Kaminski [1] reported on a new phase shift analysis of data on the reaction

$$\pi^- \, p_{\Uparrow} \rightarrow \pi^+ \, \pi^- \, n \tag{2}$$

where pions are scattered off a transversely polarised target. The data of the CERN-Cracow-Munich Collaboration covered the $\pi\pi$ energy range from 600 to

1600 MeV. Four continuous solutions were found; in the discussion here I refer to the favored "down-flat" solution. Note that we are interested in $\pi\pi$ scattering; the a_1 exchange contribution does not correspond to this situation.

A first inspection of the data shows two dips, at 980 and 1500 MeV. At these two masses intensity from $\pi\pi$ scattering is tranferred into other final states, hence at these two masses there is strong coupling from the $\pi\pi$ channel to other channels. Inspection of the complex scattering amplitude or the speed plot shows that not the two maxima but the two dips should be identified with $\pi\pi$ resonances. If we would not go to so many conferences and if would not have heard so many different ideas of how to interprete the scalar isoscalar mass spectrum, we would very naturally assign the $f_0(980)$ and the $f_0(1500)$ to the 1^3P_0 nonet.

Much of our present understanding of $\pi\pi$ scattering data goes back to the analysis by Au, Morgan and Pennington of the CERN-Munich phase shifts. In a first analysis they proposed that the continous rise of the $\pi\pi$ phase shift could originate from a broad $f_0(1000)$ while the rapid phase motion at ~ 1 GeV evidences the well known $f_0(980)$ [7]. In a detailed analysis of the $\bar{\mathrm{K}}\mathrm{K}$ threshold region using Jost functions they concluded that the pole structure of the $f_0(980)$ suggests a $\bar{\mathrm{q}}\mathrm{q}$ nature rather than a $\bar{\mathrm{K}}\mathrm{K}$ molecular state [8].

- The σ particle and the $\epsilon(1300)$

The low-mass part of $\pi\pi$ interactions is accompanied by a slow rise of the $\pi\pi$ phase shift. Recently, and at this conference, there were attempts to assign a particle to this phase shift.

Svec [1] claims the existence of a narrow σ at a mass of 750 MeV. The Crystal Barrel collaboration has tested this idea by imposing the Svec phase shift on the $5\pi^0$ final state [9]. While a good interpretation of the data was achieved using the CERN-Munich phase shifts, the fits were very poor when a narrow σ particle was imposed.

Ishida and collaborators [1] suggested a broader state. There are two essential ingradients in their analysis. The first one is a purely theoretical one: it is claimed that there is a repulsive isoscalar $\pi\pi$ background interaction just like the isotensor interaction. This background interaction introduces a slowly varying negative phase shift which reaches -90^0 at the $\bar{\mathrm{K}}\mathrm{K}$ threshold. The experimental phase motion rises slowly from zero at threshold to about $+90^0$ just below the $f_0(980)$; hence there is a $+180^0$ phase increase with respect to the background phase. This phase shift is interpreted as evidence for the σ particle. A fit to data taking the hypothetical σ particle into account leads to a greatly improved χ^2. However, the χ^2 gain comes from a better description of a small anomaly in the mass region around the $\rho(770)$ mass. Of course, the $\rho(770)$ is the most prominent contribution to low-energy $\pi\pi$ interactions. A small feedthrough from P-wave to S-wave can very well mimic this effect. The existence of a broad σ rests, in my view, entirely on theoretical arguments with at present no convincing experimental support.

If the low-mass part of the $\pi\pi$ scattering amplitude is assigned to the σ there is the need to describe intensity and phase motion above the $f_0(980)$. This was often done by postulating a $f_0(1300)$ or $\epsilon(1300)$. Au, Morgan and Pennington have shown that the σ and ϵ should be replaced by one resonance, the very broad $f_0(1000)$ with a width of $\Gamma \sim 1000$ MeV.

- Resonances and background in $\pi\pi$ scattering

The GAMS collaboration made an extremely interesting observation in the charge exchange reaction at 100 GeV/c

$$\pi^- \; p \rightarrow 2\pi^0 \; n \tag{3}$$

which helps to elucidate the nature of the $f_0(980)$. They noticed that at small values of the momentum tranfer t from the incident π^- to the outgoing $2\pi^0$ system, the $f_0(980)$ is observed as a dip just like in the $\pi\pi$ scattering data. Hence at small t the process can be seen as $\pi\pi$ scattering process. At larger t the dip structure is lost, we observe a peak instead. Appearantly, we have no longer $\pi\pi$ scattering but $f_0(980)$ meson production. The data suggest that the two different processes are governed by different interaction ranges. At momentum transfers below .1 GeV^2 or distances larger than 0.7fm, $\pi\pi$ interactions are dominated by a soft process saturating unitarity. Resonances deduce intensity to other channels and lead to dips in the $\pi\pi$ scattering amplitude. The GAMS data show that at distances of 0.5fm or smaller, $\pi\pi$ interactions are governed by production of intermediate resonances just like isovector P-wave $\pi\pi$ interactions are governed by ρ-meson formation. The soft unitarity-saturating process disappears and the cross section is much smaller.

Resonances with weak coupling to $\pi\pi$ cannot deduce intensity from $\pi\pi$ scattering, they hardly show up in $\pi\pi$ scattering data. Such resonances have to be produced in appropiate processes. The $f_0(1370)$ is an example for such resonances.

- Meson exchange in the t channel

The most likely interpretation of the soft unitarity-saturating effect seems to be the presence of t-channel exchanges. Speth and collaborators [10], Bugg and Zou [12] and Locher and collaborators [11] have shown that the slow rise of the $\pi\pi$ scattering phase shift can be understood quantitatively by ρ exchange in the t-channel. This process seems to be responsible for the soft processes dominating $\pi\pi$ interactions at large distances. When we analyse data in terms of s-channel resonances, we find a broad $f_0(1000)$ resonance. However, the pole can be produced by left-hand cuts. It is not necessary that the pole corresponds to a genuine $\bar{q}q$ bound state.

- The $f_0(980)$

There is no other particle with so many different interpretations as the $f_0(980)$. It could be a $\bar{\rm q}$q, $\bar{\rm q}$q$\bar{\rm q}$q or $\bar{\rm K}$K state, its was suggested as glueball (at a time when people believed that the $E/\iota(1440)$ was the pseudoscalar glueball); or it could be a minion, an excited state of the vacuum [13]. Also the flavor content is rather uncertain. There were new data presented at Hadron '97 which shed new light on these old questions.

The $f_0(980)$: $\bar{q}q$, $\bar{q}q\bar{q}q$ or $\bar{K}K$?

Lafferty [1] presented new results of the OPAL collaboration on production of $f_0(980)$, $f_2(1270)$ and $\Phi(1020)$ mesons in Z^0 decays. They found that the $f_0(980)$ behaves in all aspects like an ordinary meson: there is no anomalous yield per Z^0 decay, there are no significant deviations from model predictions which are based on the assumption that the $f_0(980)$ is a conventional $\bar{\rm q}$q meson; there is no anomalous production in events with low charged-particle multiplicities or with a large rapidity gap between the $f_0(980)$ and the nearest charged particle; there is no increase in the number of $f_0(980)$ in gluon jets; the particle yields in low-, middle- and high-energy jets show no significant differences. The yield of $f_0(980)$, $f_2(1270)$ and $\Phi(1020)$ mesons in hadronic decays of the Z^0 as a function of the Feynman x_p of the parton jet in which the meson is observed shows a behaviour very similar to that of the $f_2(1270)$ and the $\Phi(1020)$. Thus Z^0 decays strongly suggest that the $f_0(980)$ is a conventional $\bar{\rm q}$q state which is largely u$\bar{\rm u}$ + d$\bar{\rm d}$.

We all expected that the Φ-factory in Frascati will yield precise data on radiative Φ decays into $f_0(980)$ and $a_0(980)$. So it came as a surprise to see that Novosibirsk has good evidence for these two reactions. Assigning all events in the final state $\gamma\pi\pi$ and $\gamma\pi\eta$ to $f_0(980)$ or $a_0(980)$ production, respectively, branching fractions of

$$\begin{array}{llll} \Phi(1020)\rightarrow & \gamma f_0(980); & f_0(980)\rightarrow\pi\pi & (4.7\pm1.0)\cdot10^{-4} \\ \Phi(1020)\rightarrow & \gamma a_0(980); & a_0(980)\rightarrow\eta\pi & (1.3\pm0.7)\cdot10^{-4} \end{array}$$

are obtained. The rates are consistent with those predicted by Achasov [14] assuming that the two mesons are $\bar{\rm q}$q$\bar{\rm q}$q states.

The 2-photon fusion process $e^+e^-\rightarrow\pi\pi e^+e^-$ is dominated by tensor interactions, by the production of $f_2(1270)$. Only a very small peak due to $f_0(980)$ is seen at the $\bar{\rm K}$K threshold while there are significant contributions from $a_0(980)\rightarrow\pi\eta$. A recent analysis by Oller Berber [1] found 2-photon widths of

$$\begin{array}{lll} \gamma\gamma\rightarrow f_0(980) & f_0(980)\rightarrow\pi\pi & 0.36\ \mathrm{keV} \\ \gamma\gamma\rightarrow a_0(980) & a_0(980)\rightarrow\eta\pi & 0.32\ \mathrm{keV} \end{array}$$

Barnes [1] reminded us that the 2-photon width of the $f_0(980)$ is calculated to 2.5 keV if it is a $\bar{\rm q}$q state, and 0.6 keV if it is a $\bar{\rm K}$K molecule [15]. However we must be carefull: no other scalar state is seen in 2-photon experiments, hence we rely completely on a theory which gives a vanishing result for massless quarks as was pointed out by Close. We will see below that the calculated 2-photon width of the $f_0(1500)$ is extremely model dependent. So at present the 2-photon width is not a convincing argument in favor of the $\bar{\rm K}$K interpretation for the $f_0(980)$ or $a_0(980)$ mesons.

Törnqvist [16] proposed a unitarized quark model in which masses and widths of the lowest scalar $\bar{\rm q}$q states are grossly distorted by the opening of thresholds. Due to large couplings to $\bar{\rm K}$K and, respectively, to $\pi\pi$ and $\pi\eta$ and to other channels the pole positions are affected strongly and attracted to the $\bar{\rm K}$K threshold. The $f_0(980)$ and $a_0(980)$ are thus $\bar{\rm q}$q states with large admixtures of 2-meson-continuum states.

The flavor content of the $f_0(980)$

Surprisingly, D_s^+ decays into $\pi\pi\pi$ give valuable hints towards a better understanding of the scalar isoscalar mesons. In D_s decays, the charm quark undergoes weak decay into a s quark; hence decay modes with a $\bar{\rm K}$K pair in the final state are more prominent than decays into nonstrange mesons. D_s-mesons decay into $\pi\pi\pi$ at a small rate only. Data on this reaction were shown by Lebrun [1] and Dunnwoodie [1]. Both data agree that the $f_0(980)$ provides the most significant contribution, about one order of magnitude more than the $f_2(1270)$. Obviously the $f_0(980)$ acts as a link from the initial s$\bar{\rm s}$ to the (u$\bar{\rm u}$ + d$\bar{\rm d}$) in the final state.

A second scalar resonance is seen in this data in addition. But while Dunnwoodie argues that the data are compatible with a mass of 1400 MeV and a width of 200 MeV, Lebrun finds a mass of 1475 MeV and a width of 100 MeV from a likelihood fit to the data. The latter values are not inconsistent with the parameters of the $f_0(1500)$.

A very similar pattern had been found in J/ψ decays into $\Phi\pi\pi$ [17]. From the production process we should expect a s$\bar{\rm s}$ state recoiling against the Φ. But observed is the $f_0(980)$ in its $\pi\pi$ decay mode. Again, the $f_0(980)$ acts as a link from the initial s$\bar{\rm s}$ to the (u$\bar{\rm u}$ + d$\bar{\rm d}$) in the final state. The 2π invariant mass spectra from D_s decays into 3π and from J/ψ decays into $\Phi\pi\pi$ look very similar indicating the similarity of the underlying phyiscs. This observation was pointed out by Barnes [1].

The $f_0(980)$ summary

In my view, experimental evidence suggests that the $f_0(980)$ is a state which is mostly of $\bar{\rm q}$q nature. In particular the OPAL data on Z^0 decays seem to exclude any exotic interpretation. Radiative Φ decays and the 2-photon widths of the $f_0(980)$ and $a_0(980)$, data often used in favor of a four-quark or $\bar{\rm K}$K assignment, are in my judgement not well enough understood to enforce a non-$\bar{\rm q}$q nature.

The data on D_s decays into $\pi\pi\pi$ and on J/ψ decays into $\Phi\pi\pi$ suggest the presence of s$\bar{\rm s}$ and u$\bar{\rm u}$ + d$\bar{\rm d}$ components in the wave function. This resembles the situation in the pseudoscalar nonet where we also find strong mixing between s$\bar{\rm s}$

and $u\bar{u} + d\bar{d}$ components, between η and η'. In analogy, we should expect that also the scalar nonet is not ideally mixed and that the $f_0(980)$ and its isovector partner could have different masses. Thus the isovector partner of the $f_0(980)$ could be the $a_0(1450)$ and the $a_0(980)$ generated dynamically [10]. Alternatively, the $f_0(980)$ and the $a_0(980)$ could be isospin partners; the similarity of their masses might be an accident, enforced by the $\bar{q}q$ threshold.

Metsch presented a natural explanation for these observations [1]. In his fully relativistic model, instanton induced interactions are responsible for the mixing, both for pseudoscalar and scalar interactions.

In summary, I believe the $f_0(980)$ to be a genuine $\bar{q}q$ state the mass of which is strongly influenced by the $\bar{K}K$ threshold. It contains $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$, likely in a dominant SU(3) singlet configuration.

- The $f_0(1370)$, $f_0(1450)$, $f_0(1500)$ and $f_0(1590)$

The mass differences between these 4 resonances is obviously to small to believe that they are all independent states. Indeed, a reanalysis of the evidence for the $f_0(1450)$ [18] demonstrated that the data are also compatible with the Crystal Barrel values for mass and widths once interference with the $f_0(1370)$ was taken into account [19]. Since the $f_0(1500)$ is now confirmed in several experiments while the $f_0(1590)$ is seen only by GAMS I assume the two states to be the same. Thus we are left with two states, the $f_0(1370)$ and the $f_0(1500)$.

The first question we have to answer is why the $f_0(1370)$ is not seen in $\pi\pi$ scattering. This is possible if its coupling to $\pi\pi$ is very weak. Indeed, Thoma [1] reported that the 4π to 2π ratio is very large for the $f_0(1370)$, much larger than for the $f_0(1500)$.

The masses of the $f_0(1370)$ and $f_0(1500)$ are certainly too similar to allow to join them into one single nonet. Furthermore, both their couplings to nonstrange mesons are stronger then their couplings to $\bar{K}K$. Again, they cannot possibly belong to one meson nonet. The mass of the $f_0(1500)$ and its anomalously narrow width suggests an interpretation as ground state scalar glueball [20].

The $f_0(1370)$ and $f_0(1500)$ were brought to attention by a series of analyses of the Crystal Barrel Collaboration even though they had been hints for their existence already in previous data. We start the discussion by shortly reviewing the main results. In table 1 the product branching ratios for $\bar{p}p$ annihilation into the $f_0(1370)$ and $f_0(1500)$ and their decay into various final states are listed. We give the results for (A) the original results of the Crystal Barrel Collaboration on high-statistics data sets [21, 22, 23, 24, 9], (B) for the coupled channel analysis of the Crystal Barrel Collaboration on $\bar{p}p\to 3\pi^0$, $2\pi^0\eta$, and $\pi^0 2\eta$ [25], (C) for a combined analysis of these three final states by Bugg and collaborators [26] and (D) for new results presented at this conference by Heinzelmann and Thoma [1].

- The $f_0(1750)$ and the $f_0(2100)$

Table 1: Product branching ratios for p̄p annihilation into $\pi^0 f_0(1370), f_0(1370)\rightarrow$ mesons and $\pi^0 f_0(1500), f_0(1500)\rightarrow$ mesons in units of $10-4$ for different analyses. References are given in the text.

p̄p→	A	B	C	D
$\pi^0 f_0(1370)\rightarrow 3\pi^0$	-	-	6.4 ± 2.4	-
$\pi^0 f_0(1370)\rightarrow \pi^0 2\eta$	-	-	0.36 ± 0.22	-
$\pi^0 f_0(1370)\rightarrow \pi^0 \eta\eta'$	0	0	0	-
$\pi^0 f_0(1370)\rightarrow \pi^0 \bar{K}K$	7.0 to 18.8	-	-	-
$\pi^0 f_0(1370)\rightarrow \pi^0 4\pi$	-	-	-	-
$\pi^0 f_0(1500)\rightarrow 3\pi^0$	8.1 ± 2.8	12.7 ± 3.3	8.2 ± 0.9	-
$\pi^0 f_0(1500)\rightarrow \pi^0 2\eta$	-	6.0 ± 1.7	1.91 ± 0.24	-
$\pi^0 f_0(1500)\rightarrow \pi^0 \eta\eta'$	1.6 ± 0.4	-	1.61 ± 0.06	-
$\pi^0 f_0(1500)\rightarrow \pi^0 \bar{K}K$	3.9 to 7.7	-	-	4.52 ± 0.6
$\pi^0 f_0(1500)\rightarrow \pi^0 4\pi$	9.0 ± 1.4	-	-	-

Shen [1] presented an analysis of J/ψ radiative decays to 4π. Three scalar mesons at 1500, 1750 and 2100 MeV were used to fit the data; the analysis followed closely the reanalysis of MARKIII data on the same reaction [27]. The $f_0(1370)$ is needed in neither data.

- What is the nature of the $f_0(1370)$?

The $f_0(1370)$ is a stumbling stone. There is good evidence for the state at about 1370 MeV. Dunwoodie [1] showed data from various experiments and concluded that its mass is 1430 MeV, Bugg and collaborators find a mass of 1300 MeV [26]. Thoma [1] presented data on various $\bar{p}$N→ 5π annihilation modes and extracted a mass of 1370 MeV.

Some of the results are clearly conflicting. Crystal Barrel sees the $f_0(1370)$ dominantly in 4π and more weakly in $\pi\pi$, $\eta\eta$ and in $\bar{K}$K. The $f_0(1370)\rightarrow\pi\pi$ is seen in radiative J/ψ decays in the analysis presented by Dunwoodie [1] with a fractional yield of $(4.3^{+2.7}_{-1.7}) \cdot 10^{-4}$. Thus we should expect this state to be observed with a yield of $\sim 2 \cdot 10^{-3}$ in its 4π decay mode. At this low mass there is however not enough intensity in 4π mass spectrum from radiative J/ψ decay. The spectrum was presented by Shen [1] at this conference and can also be found in [27]. The conflict is resolved if Dunwoodie sees the $f_0(1300)$ (from elastic $\pi\pi$ scattering) and the $f_0(1500)$ (giving an effective peak at 1430 MeV), and if the $f_0(1370)$ not produced in J/ψ. It is produced in p̄p annihilation. This production selectivity hints at a multiquark interpretation for the $f_0(1370)$: it could e.g. be a $\rho\rho$ bound state. This interpretation is however also doubtfull: it does not explain its decay into $\eta\eta$ [22].

Where hides the scalar glueball ?

Peters [1] emphasized the difficulties to identify glueballs via standard arguments like production in radiative J/ψ decays and central production, or flavor symmetry in the decays. Nevertheless this discussion may serve as a guide - not as a proof - to search for fingerprints of the scalar glueball.

Before entering a detailed discussion of possible interpretations of the scalar mass spectrum I should like to emphasize the outstanding properties of the $f_0(1500)$. The $K_0^*(1430)$ and the $a_0(1450)$ have widths of 286 MeV and 260 MeV, respectively. Using SU(3) relations, the width of the $f_0(1500)$ should be 700 MeV if it is an octet state. Its observed width of 150 MeV is much too narrow, and its $\pi\pi$ partial width is 25 MeV only which is an extremely low value. This can also be seen when we compare the partial width to that of the $f_2(1270)$. The latter is about 150 MeV even though phase space and centrifugal barrier should make the $f_2(1270)$ narrower than the $f_0(1500)$.

- The 2-photon width of the $f_0(1500)$

Also the 2-photon width is very narrow. ALEPH studied 2π production in two-photon collisions and gave an upper limit of 0.17 keV for the 2-photon width of the $f_0(1500)$ (see Lafferty [1]). This value can be compared to the theoretical one of 9 keV calculated under the assumption that it is a $\bar{\rm q}$q state as given by Barnes [1]. Taken at face value, the measured 2-photon width would restrict a $\bar{\rm q}$q admixture to the $f_0(1500)$ to less than 2% and identify it as nearly pure glueball. On the other hand, the presence of the $\eta\eta'$ decay mode and the smallness of the coupling to $\bar{\rm K}$K proves that the $f_0(1500)$ also cannot be a pure glueball. Certainly it is not a s$\bar{\rm s}$ quarkonium state. Metsch [1] in his relativistic quark model gives a 2-photon width just compatible with the upper limit. Obviously, care has to be taken to arrive at conclusions in a too straightforward manner.

- Production in radiative J/ψ decays

When the $f_0(1500)$ is a glueball then it must be produced in radiative J/ψ decays. Its appearant non-observation in those experiments was therefore an intruiging argument against the possibility that it should contain at least a large glueball component. A closer look at the J/ψ data reveals that the $f_0(1500)$ is produced in radiative J/ψ decays but escaped its discovery.

Data on radiative J/ψ decays into 4π show a distinct peak at 1500 MeV to which pseudoscalar quantum numbers had been assigned. In a recent reanalysis [27] it was shown that the data prefer scalar quantum numbers. The analysis was guided by E760 data which had convincing peaks in their $\eta\eta$ mass spectrum at 1500 MeV, 1750 MeV and at 2100 MeV. Obviously, these peak cannot be due to pseudoscalar resonances; the partial wave analysis of the MARKIII data demonstrated that the data are at least compatible with scalar quantum numbers for the 3 states.

The analysis has an important issue: it demonstrates that likely the $f_0(1500)$ was produced in radiative J/ψ decays. A carefull inspection of data on J/ψ

$\rightarrow \pi\pi$, $\eta\eta$ and into 4π evidences small peaks at 1500 MeV in all three mass projections [28]. The data provide certainly no conclusive evidence for a scalar resonance at this mass but they can also not be used as argument against production of the $f_0(1500)$ in radiative J/ψ decays. Close and Farrar [29] have argued recently that the production rate of not too broad scalar glueballs in J/ψ decays should be small, in the order of 10^{-3}. This value is not incompatible with the experimental findings.

- The "glueball filter" of Close and Kirk

Central production is believed to be a good place for a glueball search. It is known that at very large momenta no mesons or quark lines are exchanged in Central Production. The process is mediated by the exchange of Pomerons; particles which incorparate a large fraction of glue.

Kirk [1] showed at the conference that the resonance pattern in Central Production depends significantly on the transerve momentum balance, on a quantity ΔP_T: the two protons may collide and be scattered into opposite directions so that the difference of the two transverse momenta p_T becomes large. This is a configuration in which well-established $\bar{\mathrm{q}}\mathrm{q}$ mesons are observed with large production cross sections. With a cut excluding large differences between transverse momenta – a configuration in which gluons from Pomerons might fuse into glueballs – production of conventional $\bar{\mathrm{q}}\mathrm{q}$ states is suppressed; states which have been discussed as non-$\bar{\mathrm{q}}\mathrm{q}$ objects remain however visible in the data. Close and Kirk [30] suggest that the ΔP_T cut suppresses conventional $\bar{\mathrm{q}}\mathrm{q}$ states but not the production of glueballs.

Of course, with vanishing relative linear momenta also the relative orbital angular momentum vanishes, and one might expect enhancement of scalar states in comparison to other $\bar{\mathrm{q}}\mathrm{q}$ configurations. The argument rests therefore very much on the reality of the $f_2(1950)$ proposed by WA102, since this is the only non-scalar particle surviving the glueball filter.

Scalar states which are identified as 'gluish' by the Close-Kirk filter are the $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and the $f_0(1710)$, i.e. all scalar states (the production cross section for the $f_0(2100)$ is too small to make any statements here). The gluonic component seems to be distributed democratically over the full mass range. Close and Kirk interprete the filter as anti-$\bar{\mathrm{q}}\mathrm{q}$ filter, also selecting multiquark or $\bar{\mathrm{K}}\mathrm{K}$ states and restrict the glueball content to the three higher mass states. This interpretation seems artificial to me.

- Glueball quarkonia mixing schemes

Amsler and Close analysed the $f_0(1500)$ decays and found that its decay pattern is incompatible with a interpretation of the state being a pure glueball. But it is also incompatible with the hypothesis that it is a $\bar{q}q$ state independent of the scalar mixing angle [1] [20]. The decay pattern can only be reproduced

[1] The statement is no longer strictly true since the $f_0(1500)\rightarrow\bar{\mathrm{K}}\mathrm{K}$ decay branching ratio is now known to be larger than the upper limit given in a bubble chamber analysis.

when mixing of the $f_0(1500)$ with the $f_0(1370)$ and a $f_0(\bar{s}s)$ is introduced. The necessity of a scalar s$\bar{\text{s}}$ state follows from the following argument: We have two states, the $f_0(1370)$ and the $a_0(1450)$, which are nearly degenerate in mass. This fact suggests that the scalar mixing angle may be close to the ideal one. The $f_0(1710)$ (if it is a scalar) could possibly be the missing s$\bar{\text{s}}$ state; Amsler and Close suggest that the s$\bar{\text{s}}$ state could be missing. In this scenario the $f_0(1500)$ is a glueball mixing with closeby scalar isoscalar states but with a large glueball component. The $f_0(1370)$ and the f_0(s$\bar{\text{s}}$) are mainly $\bar{\text{q}}$q states with some glueball content.

Other mixing schemes are proposed since then: in Weingarten's scheme the $f_0(1710)$ has more glue than $f_0(1500)$ [31]; Anisovich [1] finds 5 scalars below 1800 MeV, one glueball and two nonets (1^3P_0 and 2^3P_0) which are all mixed. Narison [32] allows the $f_0(1370)$, $f_0(1500)$, and the $f_0(1710)$ to share glue democratically. Kisslinger [33] reported sum rule calculations in which the bare glueball mass is found at a mass of 300 to 600 MeV. Yet a small (20%) admixture of a $\bar{\text{q}}$q scalar meson allows to bring up the mass to 1500 MeV.

So even when the precise mixing is not yet well understood, the analyses agree that a scalar glueball has intruded into the spectrum of scalar mesons. Most authors find a mass of the bare glueball at about 1600 MeV. This agrees (maybe too) nicely with lattice gauge calculations for which Michael [1] reported a mass of $(1611 \pm 30 \pm 160)$ MeV.

5 TENSOR MESONS AND THE TENSOR GLUEBALL

Lattice gauge calculations suggest that the tensor glueball should have a mass which is larger than the mass of the scalar glueball by a factor ~ 1.4 leading to an expected mass value of $(2232 \pm 220 \pm 220)$ MeV for the bare tensor glueball mass. We shortly review the status of tensor mesons.

The AX(1565) meson

The AX(1565) was dicovered in $\bar{\text{p}}$p annihilation at rest in its decay into $\pi^+\pi^-$ [34]. The ASTERIX collaboration tagged events with P-state annihilation by observation of X-rays of $\bar{\text{p}}$p atoms formed after capture of antiprotons in hydrogen. Thus they could show that the AX(1565) was mainly produced from P-states of the $\bar{\text{p}}$p atom and not from S-states [35]. Later the Crystal Barrel collaboration discovered in $\bar{\text{p}}$p annihilation into $3\pi^0$ a predominant contribution from a scalar meson at about the same mass, of the $f_0(1500)$ [36]. A tensor contribution was required consistently in all anlyses but the evidence was less convincing. So the fate of the AX(1565) remained somewhat unclear.

The OBELIX collaboration developed the technique of varying the target density: in liquid H_2 there is 90% S-state capture, at atmospheric pressure there is 50% S-state, 50% P-state capture, and P-state capture is dominant for H_2 targets of a few mbar pressure.

Rotondi and Vecchi [1] presented data on p̄p annihilation at rest into $\pi^+\pi^-\pi^0$ in liquid H_2, gaseous H_2 at normal pressure and temperature and in low-pressure gas. The simultaneous fit to the 3 data sets evidenced contributions of both, the AX(1565) and the $f_0(1500)$ with the former mainly produced from P-states, the latter from S-states.

Further evidence for the state in its $a_2(1320)\pi$ decay mode produced by charge exchange in a 37 GeV/c pion beam was shown by Zaitsev [1]. The tensor contribution raises from 1500 MeV to its maximum value at $\sim$ 1580 MeV; the state is obviously the same as the tensor reported before by GAMS and VES in the $\omega\omega$ and $\rho\rho$ decay modes. On the other hand, Asterix [37] found no evidence for the AX(1565) in 4 π decays. Thoma [1] showed Crystal Barrel data evidencing a weak 4π contribution, likely in $a_(1320)\pi$.

The AX(1565) was interpreted as NN̄ bound state [38] since it was seen as strong effect in p̄p annihilation and since its properties match nicely with expectations from NN̄ models [39]. In NN̄ models we expect only an isoscalar state; isovector states are expected to have larger masses. There is, however, also evidence for a $a_2(1650)$ [25, 41] in p̄p annihilation. A tensor meson nonet at this low mass is, of course, unexpected. It might contain the Θ if that is a tensor.

The $\Theta(1690)$

Gutierrez reported on an attempt to resolve the spin ambiguity of the $\Theta(1690)$ or $f_j(1710)$ [1] in proton-proton central production of $K^0_sK^0_s$ at Fermilab (E690). Above 1.56 GeV $K^0_sK^0_s$ mass there are four solutions two of which could be ruled out. The remaining two solutions show a strong signal from $f_0(1500)$ in both solutions, the absence of the $f_2(1525)$ is unexpected. Both solutions show a very good evidence for a resonance at about 1700 MeV, but in one solution it has scalar, in the other solution tensor quantum numbers.

A reanalysis of MARKIII data on radiative J/ψ presented by Dunwoodie [1] argued in favor of 0^{++} for the Θ while Bugg [1] used the state to complement a tensor meson nonet consisting of the AX(1565), the $a_2(1650)$ and a missing K^*_2. His arguments in favor of the 2^{++} assignment were the discovery paper of MARKIII, the OMEGA results, a recent (still preliminary) analysis of Crystal Barrel in-flight data on p̄p$\rightarrow K^+K^-\pi^0$, the ambiguous E690 Fermilab data, and a reanalysis on J/ψ radiative 4π production data [27].

$\Phi\Phi$ resonances

The 3 $\Phi\Phi$ tensor resonances with masses between 2000 and 2400 MeV are with us since more than a decade [46] while at most 2 states are expected from the quark model. The lowest-mass partner is within errors compatible with a tensor state – proposed by Kirk and collaborators at 1950 MeV – which survives the Close-Kirk glueball filter [1].

The $\xi(2220)$

Ever since the claim of the MARKIII collaboration of a very narrow state in radiative J/ψ decays into $\bar{\mathrm{K}}$K, the $\xi(2220)$ has attracted the speculative interest [44] even though its existence was questioned by DM2 data on the same reaction [45]. A $\bar{\mathrm{q}}$q state at this mass is espected to have a width of several hundreds of MeV, much broader than the 10 to 40 MeV found by MARKIII. Its mass is close to the expected tensor glueball mass; it is thus a strong candidate for glueball hunters. Its nonobservation in antiproton-proton collisions allowed to put tight upper limits on the branching fraction of this state into $\bar{\mathrm{p}}$p. But this result did not question its existence as long as $\xi\to\bar{\mathrm{p}}$p was not observed. This is now the case and changes the picture considerably. The state is discussed here as tensor even though its spin is not known and not even its existence is granted.

The BES collaboration provided new evidence for this state in several final states including the decay into $\bar{\mathrm{p}}$p. From the data we may estimate a total yield by accounting for unobserved charge-related decay modes like $\mathrm{K}_l^0\mathrm{K}_l^0$, $\bar{n}n$ and unmeasured 4π decays, and find

$$Br(\mathrm{J}/\psi\to\gamma\xi(2220)) \sim\ 2.8\times\ 10^{-4} \tag{4}$$

with $\xi\to 2\pi$, 4π, N$\bar{\mathrm{N}}$. Assuming SU(3) symmetry, the decays into $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ (for which upper limits only are given) contribute insignificantly to this rate.

The $\xi(2220)$ is not observed in $\bar{\mathrm{p}}$p annihilation. At present, the most significant published evidence from PS202 is

$$Br(\bar{\mathrm{p}}\mathrm{p}\to\xi(2220))\cdot Br(\xi\to K_s^0K_s^0) \leq\ 7.5\times\ 10^{-5} \tag{5}$$

However, the $\xi(2220)$ does decay into $\bar{\mathrm{p}}$p. These two observations can only be reconciled if the total yield of $\xi(2220)$ in radiative J/ψ decays is

$$Br(\mathrm{J}/\psi\to\gamma\xi(2220)) \geq\ 2.3\times\ 10^{-3} \tag{6}$$

Hence there must be other decay modes of the $\xi(2220)$ with very large branching fractions which seems to be unlikely.

On the other hand, there is independent evidence from LEP reported by Lafferty [1]. The $\mathrm{K}_s^0\mathrm{K}_s^0$ invariant mass distribution shows a prominant peak at about 2.2 GeV for K_s^0 pairs produced in three-jet events. Interesting enough, the signal is absent in two-jet events, hence one is tempted to assign the signal to the presence of a gluon jet. The width of the state cannot be determined; it is however compatible with experimental resolution ($\sim$ 200 MeV).

A way out of this conflict between the appearant existence of the $\xi(2220)$ and its non-observation at LEAR is to assume that the $\xi(2220)$ is not as narrow as reported. Visually, the data are suggestive of a narrow state, but this interpretation requires the presence of other closeby narrow states the mass of which is different in the various final states. The data seem to be also compatible with the existence of one state with $\Gamma \sim 200$ MeV. No upper limit for production of a state of this width can presently be derived from $\bar{\rm p}$p annihilation data.

In view of the incompatibilty of the existence of a narrow $\xi(2220)$ with the reported $\bar{\rm p}$p branching ratio and its nonobservation in $\bar{\rm p}$p annihilation at LEAR I conclude that the $\xi(2220)$ width must be broader than reported. The data on radiative J/ψ decays seem not to contract this hypothesis.

Is the tensor glueball very broad ?

Bugg suggested at this conference [1] a scenario in which a very broad 2^{++} glueball with a mass of about 1950 MeV and a width of 450 to 650 MeV mixes strongly with the Θ and the $\Phi\Phi$ states of Lindenbaum and collaborators. The new WA102 state at 1950 MeV signaling its share of glue by surviving the Close-Kirk filter may be used to support this idea. A similar scheme - wide glueball mixing with $\bar{\rm q}$q states - was proposed by Bugg and by Zou [42] for the pseudoscalar sector.

6 $\mathbf{J^{PC} = 1^{-+}}$ exotic mesons

- Summary of observations on $\mathrm{J^{PC}} = 1^{-+}$ exotics

Experimental evidence for an exotic $\mathrm{J^{PC}} = 1^{-+}$ wave was reported at Hadron '97 by BNL E852, by VES and by the Crystal Barrel collaboration. Before going into a more detailed discussion of the different observation, I present in Table 2 the results obtained by the 3 groups.

- **P-wave in the $\pi\eta$ system**

Ostrovidov [1] (BNL E852) and Zaitsev [1] (VES) reported on phase shift analyses of the $\pi\eta$ and $\pi\eta'$ systems produced by isoscalar exchange (likely $f_2(1270)$ or Pomeron exchange). Amplitudes and phases of the P-wave are determined relative to the (dominant) D-wave, i.e. relative to the well-established $a_2(1320)$. Intensity and phase of the 1^{-+} wave in both experiments are fully compatible; plotted on one common graph they look like stemming from a single experiment. The similarity of the results demonstrates that experiments and analysis techniques are well understood and give reproducible results. BNL E852 fits the data under the assumption that there is a resonance; they get an excellent fit with mass of $(1370 \pm 16^{+50}_{-30})$ and width of $(385 \pm 40^{+65}_{-105})$ MeV.

Table 2: Summary of observations on a $J^{PC} = 1^{-+}$ exotic wave

		E852	VES	CBAR
$\eta\pi$	M	$1370 \pm 16^{+50}_{-30}$	$(\eta + \eta')\pi$	$1400 \pm 20 \pm 20$
	Γ	$385 \pm 40^{+65}_{-105}$	see below	$310 \pm 50^{+50}_{-30}$
$\eta'\pi$	M	~ 1600	$1572 \pm 18 \pm 10$	-
	Γ	-	$550 \pm 57 \pm 20$	-
$\rho\pi$	M	$1593 \pm 8 \pm ?$	not seen	-
	Γ	$168 \pm 20 \pm ?$		-
$f_1\pi$	M	$\sim$ 1600 − 2000	signal,	-
	Γ	0 or 2 resonances	no phase motion	-

Dünnweber [1] showed Crystal Barrel results on the reaction $\bar{p}n \to \pi^-\pi^0\eta$. There is a strong signal from $\rho^-\eta$ and large contributions from $a_2(1320)\pi$ in both $\eta\pi$ charge combinations. The forward-backward asymmetry in the $\pi\eta$ system requires introduction of a resonant $\pi\eta$ P-wave; the fit optimizes for mass of $(1400 \pm 20 \pm 20)$ and a width of $(310 \pm 50^{+50}_{-30})$ MeV in full agreement with the BNL852 and VES results. Similar results are obtained from annihilation in liquid and gaseous hydrogen.

The GAMS collaboration represented by Lednev [1] studied the charge-exchange reaction $\pi^-p \to \eta\pi^0 n$ at 32, 38 and 100 GeV/c. While confirming a significant contribution from an odd $\pi\eta$ wave they do not find a resonance contribution. The result is not necessarily in disagreement with those on the $\eta\pi^-$ system. The $\pi_1(1370)$ may be produced only via Pomeron exchange; then it cannot turn up in the GAMS analysis. This is in agreement with BNL findings: they also observe no resonance in the $\pi^0\eta$ final state.

- **P-wave in the $\pi\eta'$ system**

Again, the data from BNL and Serpukhov agree very well on the P-wave in $\pi\eta'$ while in this case Crystal Barrel is not sufficiently sensitive to identify the P-wave. The BNL results are tentatively interpreted as evidence for a second $J^{PC} = 1^{-+}$ exotic resonance at a mass of about 1600 MeV. The mass and phase motion agree with observations in the $\rho\pi$ channel.

- **Is there a $J^{PC} = 1^{-+}$ exotic in $\rho\pi$?**

It is here that BNL E852 and VES observations are different. The E852 collaboration suggests a $J^{PC} = 1^{-+}$ exotic wave in $\rho\pi$ resonating at 1600 MeV. It is observed in both $\pi^+\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ final states. Since this resonance decays into $\rho\pi$ it must also be produced in pion scattering off ρ mesons, in isovector exchange reactions. Zaitsev [1] reported that they have had evidence for a $\rho\pi$ exotic, too. Yet the signal disappeared when they allowed rank 2 in the fitting procedure. The scattering process is considered rank 1 when it is described by at most 2 incoherent processes, for spin flip and spin non-flip. Rank 2 allows that the unobserved nucleon is excited leading to a second pair of incoherent production processes. The BNL group argues that rank 2 is not required in their data since the sum of some nonvanishing amplitudes is very small, compatible with zero, which is not possible for incoherent processes. VES finds, however, that the data are well described without an exotic $\rho\pi$ wave when rank 2 is allowed even though is magnitude is small only, at the 10% level.

- **The $f_1(1285)\pi$ channel**

Also in this channel, BNL and VES data require consistently an exotic $f_1(1285)\pi$ P-wave but do not find a clear phase motion.

- **A global view of the $J^{PC} = 1^{-+}$ wave**

The BNL group suggests the existence of several $J^{PC} = 1^{-+}$ resonances: at 1370 MeV produced by isoscalar exchange and decaying into $\pi\eta$, at 1600 MeV produced by isovector exchange and observed in its decay into $\eta'\pi$ and into $\rho\pi$, and possibly 2 further states in the region from 1600 to 2000 MeV. The argument in favor of more than one resonance are the different production mechanisms.

Zaitsev suggests that there one exotic $J^{PC} = 1^{-+}$ wave in $\pi\eta$, in $\pi\eta'$ and in $f_1(1285)\pi$ but that it is nonresonant or that the width is rather broad. The resonance-like phase motion of the $\pi_1(1400)$ is ascribed to the $f_1(1285)\pi$ threshold and a strong coupling to it. This is, of course, a very important issue which must be clarified experimentally. The Crystal Barrel Collaboration allowed for a coupling to $f_1(1285)\pi$ in their fit to the exotic $\pi\eta$ wave but at most a small coupling was found.

There is a further possibility to decide which of these two different scenarios is correct and which one is faulty. The $\pi_1(1400)$ is produced only via isoscalar exchange not in charge exchange reaction. The $\pi_1(1400)$ however must also be produced via isovector exchange since it decays into $\rho\pi$. The resonance must therefore also be observable also in ρ-exchange and hence in charged exchange reactions. Thus the $\pi_1(1600)$ must be observable in $\eta'\pi^0$ not only in $\eta'\pi^-$. Remember that the $\pi_1(1400)$ is seen only in $\eta'\pi^-$ and not in $\eta'\pi^0$.

At present my personal preference is to believe that the $J^{PC} = 1^{-+}$ exotic wave is there, is related to glue but rather broad. The wave is seen in $\eta\pi^-$, in $\eta'\pi^-$ and in $f_1(1285)\pi^-$. Cusps at threshold openings give it an appearant phase motion which the sum of the amplitudes may not have. Clearly, this view is in contradiction to the weak $f_1(1385)\pi$ coupling found by Crystal Barrel and to the BNL $\rho\pi$ exotic wave.

7 Gluon degrees of freedom in meson spectroscopy

Quantum Chromo Dynamics, the theory of strong interactions, requires the existence of new forms of hadronic matter [47]. Glueballs should exist, meson resonances without constituent quarks composed of gluons bound together due to the non-abelian character of the interaction. And hybrids should exist in which a $\bar{q}q$ pair in color octet is color-neutralised by a constituent glue. Where do we stand with respect to these pretentious claims?

There are too many scalar mesons: the $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1750)$ and, possibly, a $f_0(2100)$. Below 1.7 GeV there is no $s\bar{s}$ state. An attractive solution is therefore to interprete the $f_0(980)$ as $\bar{K}K$ molecule and to postulate an additional $s\bar{s}$ state at 1600 MeV [20]. (The $f_0(1750)$ could potentially play this role but its strong coupling to non-$\bar{K}K$ decay modes makes this option unlikely.) Then there are 4 states in a 400 MeV mass intervall: there must be a glueball mixing in.

The missing link in this game, the $s\bar{s}$ state at 1600 MeV, can be circumvented when one follows models introducing instanton-induced interactions. In this case, the $f_0(980)$ is not a $\bar{K}K$ molecule but a genuine $\bar{q}q$ state. The scalar nonet mixing makes the $f_0(980)$ to a dominant SU(3) singlet state while the octet state has higher mass; it could be the $f_0(1370)$ or the $f_0(1500)$. Two high-mass states remain, the $f_0(1750)$ and the $f_0(2100)$, and the $f_0(1370)$ or the $f_0(1500)$ is supernumerous.

The $f_0(1370)$ plays an important role in this chain of arguments. A minimal solution without it would assign the $f_0(980)$ and $f_0(1500)$ to the 1^3P_0 and the $f_0(1750)$ and $f_0(2100)$ to the 2^3P_0 nonets. In this case the $f_0(1370)$ would be interpreted as, e.g., $\rho\rho$ resonance or as generated by meson exchange dynamics. This assumption is in line with the non-observation of a strong 4π intensity at 1370 MeV in radiative J/ψ decay.

Without $f_0(1370)$ there is no proliferation of f_0 states. The role of glue in the scalar mass spectrum then relies on dynamical arguments: in radiative J/ψ decays, the strongest scalar activity is at 1430 and at 1700 MeV. In central production, there is affinity to glue over the full mass range from 1 to 1.75 GeV. Scalar glue-glue interactions do not lead to formation of a new state, of a narrow glueball, but rather enhance the production of scalar $\bar{q}q$ mesons by mixing with them in gluon-rich enviroments. This view seems to be supported by the conjecture of Bugg and Zou [42] in their interpretation of the spectrum of pseudoscalar and tensor resonances in radiative J/ψ decays.

Similar conclusions emerge from the discussion of the 1^{-+} exotics. One possible scenario is a series of states decaying into $\eta\pi$, $\eta'\pi$ or $\rho\pi$, and into $f_1(1285)\pi$. A global view of this wave suggested however that the different pieces might be part of one non-resonating wave or a very broad state.

The role of gluons in spectroscopy is in my opinion much less direct than we had naively hoped. Gluons manifest themselves in allowing exotic waves but we should be prepared that there is no strong signal sticking out. The selfinteraction of gluons manifests itself by mixing broad objects into spectroscopy, more visible in dynamics than in spectroscopy.

Was the search for glueballs and hybrids in vain? I certainly do not believe so. There is certainly a much improved understanding of the scalar meson nonet. Its eminent role for meson spectroscopy is beginning to be elucidated. There is now substantiated hope that the 'scalar meson enigma' will finally be lifted.

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