Hadron Spectroscopy

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The experimental status of glueballs and hybrids is briefly reviewed. Recent results for scalar mesons suggest that $f_0(1500)$ is the ground state scalar glueball. The identification of the first excited glueball state, a tensor, is premature, although candidates are available. We have now evidence for at least two mesons, $\pi_1(1400)$ and $\pi_1(1600)$, with quantum numbers incompatible with a $q\bar{q}$ structure.

1. INTRODUCTION

Hadron spectroscopy is a very active field with the recent discovery of new light and heavy quark mesons and baryons. A comprehensive review within the scope of this conference is clearly not possible. I shall therefore report on salient and exciting new results pertaining to *light quark and exotic mesons* obtained in $\bar{p}p$ annihilation at CERN/LEAR, in pp central production at the CERN-SPS, in πN scattering at Serpukhov and Brookhaven, in e^+e^- annihilation at Novosibirsk and in $\gamma\gamma$ collisions at Cornell and LEP .

Consider $q\bar{q}$ mesons made of the light u, d, s quarks which are grouped in nonets with quantum numbers $n^{2s+1}\ell_J(J^{PC})$, with obvious notation, and where $P = (-1)^{\ell+1}$, $C = (-1)^{\ell+s}$. The ground states $1^1S_0(0^{-+})$ and $1^3S_1(1^{--})$ are well established. There are established mesons for the first orbital excitations $1^3P_1(1^{++})$, $1^3P_2(2^{++})$ and $1^1P_1(1^{+-})$, but the classification of *scalar* mesons $1^3P_0(0^{++})$, which we shall discuss below, remains controversial. The general trend for the width is to increase with mass and therefore higher radial ($n > 1$) and orbital ($\ell > 1$) excitations, with mass above 2 GeV, are hard to observe, although candidates with spins as high as $J = 6$ have been reported [1].

2. GLUEBALLS AND HYBRIDS

Of particular interest are the two isospin $I = 0$ mesons made of $n\overline{n} \equiv 1/\sqrt{2}(u\overline{u} + d\overline{d})$ and $s\overline{s}$ pairs, or a mixture thereof. The states made only of gluons, the glueballs of QCD, are also isoscalars. Lattice calculations predict that glueballs with *exotic* J^{PC} (0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, etc, that cannot be generated with $q\bar{q}$ pairs) lie in the difficult region above 2 GeV [2]. Figure 1 shows a compilation of results from the lattice as a function of lattice spacing a. When the scale parameter r_0 (estimated from the string tension in heavy quark mesons) is taken to be about 0.5 fm one finds by extrapolation to $a = 0$ a mass of 1611 $\pm$ 30 $\pm$ 160 MeV for the ground state glueball, a scalar (0^{++}), while the first excited state is tensor (2^{++}) and has a mass of 2232 $\pm$ 220 $\pm$ 220 MeV [3]. The first error is statistical while the second error reflects the uncertainty on r_0.

Hence the low mass glueballs lie in the same mass region as ordinary isoscalar $q\bar{q}$ states, that is in the mass range of the $1^3P_0(0^{++})$ and $2^3P_2, 3^3P_2$, $1^3F_2(2^{++})$ states. This is why a detailed understanding of the $q\bar{q}$ nonets is mandatory. We shall argue below that significant progresses have been made recently for scalar mesons to identify the 0^{++} glueball, while much uncertainty remains for the 2^{++} assignment.

The lattice calculations assume that the quark masses are infinite and therefore neglect $q\bar{q}$ loops. However, one expects that glueballs will mix with nearby $q\bar{q}$ states of the same quantum numbers [4]. The effect of $q\bar{q}$ loops on the glueball mass is not clear and the size of the $q\bar{q}$ admixture in the glueball wavefunction is not predicted by lattice calculations. However, one would still find three isoscalar states in the regions of the 0^{++} and 2^{++} nonets, instead of only two.

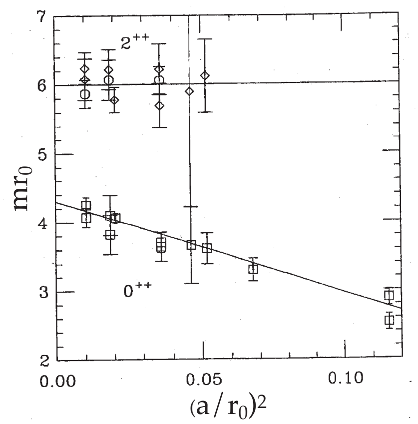

Figure 1. Predictions for the mass m of the ground state glueball (0^{++}) and for the first excited state (2^{++}); a is the lattice spacing and r_0 is a scale parameter, see text (from ref. [3]).

Hybrids can be pictured as $q\bar{q}$ mesons with the binding gluons in a vibrating mode. In contrast to glueballs, they can have both isospin 0 and 1. The mass spectrum of hybrids with exotic quantum numbers was predicted in ref. [5] while ref. [6] also deals with non-exotic quantum numbers. Exotic hybrids (0^{+-}, 1^{-+} and 2^{+-}) are expected around 1.9 GeV. Most of them are rather broad but some can be as narrow as 100 MeV. They prefer to decay into a pair of S- and P-wave mesons, like $\pi f_1(1285)$, $\pi b_1(1235)$ and $\pi f_0(1370)$. Lattice calculations predict that the hybrid with exotic quantum numbers 1^{-+} lies at a mass of 1.9 ± 0.2 GeV [7]. Obviously, exotic hybrids do not mix with $q\bar{q}$ states.

2.1. SEARCHING FOR THE 0^{++} GLUEBALL

There are too many scalar mesons to fit in the ground state 0^{++} $q\bar{q}$ nonet: the $a_0(980)$ and $a_0(1450)$ in the $I = 1$ sector, the $f_0(400-1200)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ in the $I = 0$ sector and the $K_0^*(1430)$ in the $I = 1/2$ sector. While the $a_0(980)$, $f_0(980)$ and $K_0^*(1430)$ were established a long time ago, the other states were discovered more recently thanks to new experimental techniques and high statistics data samples. Let me deal first with the $a_0(980)$ and $f_0(980)$ mesons.

2.2. The $a_0(980)$ and $f_0(980)$ mesons

The $a_0(980)$ decays mainly into $\eta\pi$ while the $f_0(980)$ decays mainly into $\pi\pi$. However, their decay fractions to $K\bar{K}$ are rather large (for instance 20% for the a_0 [8]) although this mode should be suppressed by the nearby $K\bar{K}$ threshold. This indicates that their wavefunctions must contain a significant fraction of $s\bar{s}$ which is excluded for an isovector $q\bar{q}$ state like $a_0(980)$. These mesons have been proposed as four-quark states ($s\bar{s}(d\bar{d}-u\bar{u})$ and $s\bar{s}(d\bar{d}+u\bar{u})$, respectively) [9] or as $K\bar{K}$ molecular states [10].

It is sometimes argued that molecular states should have much smaller $\gamma\gamma$ widths than $q\bar{q}$ states. The expected $\gamma\gamma$ widths for $q\bar{q}$ mesons can be estimated using the measured widths for 2^{++} mesons, using the (relativistic) formula [11]

$$\Gamma_0 \simeq 2\,\Gamma_2 \left(\frac{m_0}{m_2}\right)^3 . \tag{1}$$

One finds $\sim$ 1 keV for a_0 and $\sim$ 0.1 keV for f_0 (assuming $s\bar{s}$). More sophisticated calculations lead to 0.64 keV [12] and 0.3 - 0.5 keV [12,13], respectively, which is similar to the widths of molecular states ($\sim$ 0.6 keV for the a_0 [14]). Hence measurements of the $\gamma\gamma$ widths cannot distinguish between molecular and $q\bar{q}$ states. The experimental values are, in fact, 0.30 $\pm$ 0.10 [1] and 0.56 $\pm$ 0.11 keV, respectively [15].

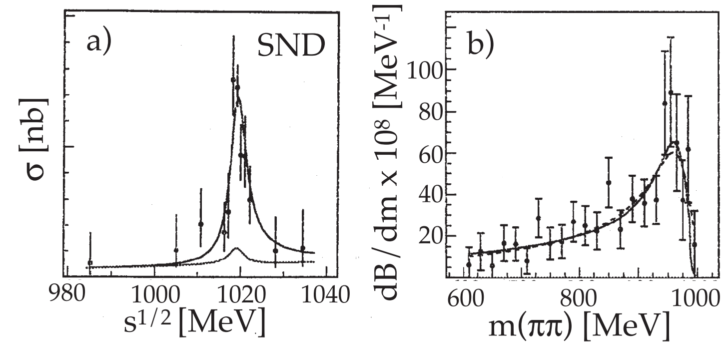

Figure 2. Cross section for ϕ production in $e^+e^- \rightarrow \pi^0\pi^0\gamma$ (a) and $2\pi^0$-mass distribution (b) (from ref. [17]).

An alternative method is radiative ϕ decay into a_0 and f_0: $K\bar{K}$ molecules should be produced with a branching ratio of 10^{-5} in radiative ϕ decay, while $f_0(980){=}s\bar{s}$ and $a_0(980){=}n\bar{n}$ should be produced with a rate of 5×10^{-5} and 5×10^{-6}, respectively [16]. One the other hand, four-quark states ($qq\bar{q}\bar{q}$) would be produced with a much larger rate of 10^{-4}. The first measurements from radiative ϕ decay into $f_0\gamma$ and $a_0\gamma$ are available from the e^+e^- VEPP-2M ring at Novosibirsk. Figure 2a shows the excitation function for $e^+e^- \rightarrow \phi \rightarrow \pi^0\pi^0\gamma$ and fig. 2b the $\pi^0\pi^0$ mass distribution at the ϕ from the SND experiment [17]. The enhancement below 1000 MeV (fig. 2b) is due to $f_0(980) \rightarrow \pi^0\pi^0$.

The fit leads to a branching ratio for $\phi \to f_0\gamma \to \pi\pi\gamma$ of $(3.42 \pm 0.49) \times 10^{-4}$. For $\phi \to a_0\gamma \to \eta\pi^0\gamma$ SND finds [18] the branching ratio $(0.83\pm0.23)\times10^{-4}$. The other experiment (CMD-2) reports similar values [19]. These important results should be verified at the DAϕNE facility.

From the large production rates one can conclude that $a_0(980)$ and $f_0(980)$ are four-quark states, eventhough not everybody agrees [13,20]. Indeed, $f_0(980)$ is strongly produced in the $D_s^+(c\bar{s}) \to \pi^+\pi^+\pi^-$ decay [21], which points to a large $s\bar{s}$ component (Cabibbo favoured decay), although some $n\bar{n}$ must be present for $\pi\pi$ decay. In contrast, f_0 is observed in hadronic Z^0 decays with cross sections similar to those for $n\bar{n}$ states [22]. However, the production cross section of four-quark states is not known.

2.3. The $\mathbf{f_0}$(400-1200) meson (or $\boldsymbol{\sigma}$)

The pure $I = 0$ $\pi\pi$ S-wave is not easy to measure since the $\pi\pi$ system is dominated by the P-, D-, and F-waves, $\rho(770)$, $f_2(1270)$ and $\rho_3(1690)$. The low energy range is derived from pion production data in $\pi^-p \to \pi^+\pi^-n$ at 17 GeV [23] and requires strong assumptions on the amplitudes due to the large number of parameters. A reanalysis of these data, together with pion production data on polarized target and using much weaker assumptions, was published recently [24]. There is a fourfold ambiguity for the S-wave phase shift below 1 GeV: the two solutions that show a rapid phase shift variation around 800 MeV and lead to a *narrow* σ resonance are not plausible as they are associated with a peculiar oscillation of the elasticity parameter below 950 MeV. The two slowly varying solutions (called "up flat" and "down flat") are both acceptable and lead to a *broad* σ ($M = 506 \pm 10$, $\Gamma = 494 \pm 5$ MeV [25]). Hence a narrow σ appears to be excluded. It is also not observed in the very high statistics $3\pi^0$ Dalitz plots from Crystal Barrel [26].

A very broad structure with mass varying between 400 and 1200 MeV is observed in the $\pi\pi$ S-wave by many other experiments, in particular low energy $\bar{p}p$ annihilation [15]. The interpretation of the σ as a $q\bar{q}$ resonance is, however, controversial. It could be a (mostly $n\bar{n}$) $q\bar{q}$ state, a meson-meson resonance [27], or could be due to t-channel ρ exchange [28].

2.4. The $\mathbf{a_0}$(1450), $\mathbf{f_0}$(1370) and $\mathbf{f_0}$(1500) mesons

The isovector scalar state $a_0(1450) \to \eta\pi$ that was discovered by Crystal Barrel at LEAR in the annihilation channel $\pi^0\pi^0\eta$ was also observed by Crystal Barrel to decay into $\eta'\pi$, $K^0\bar{K}^0$ and $K^0K^\pm$ [15]. Its mass (1474 MeV) and width (265 MeV) are consistent for all decay modes and its decay branching ratios agree with SU(3) predictions for a $q\bar{q}$ scalar state [15]. The evidence for $a_0(1450)$ confirms theoretical expectations that the mass scale for the ground state scalar $q\bar{q}$ mesons is 1300 - 1400 MeV [29], and strengthens the interpretation of $a_0(980)$ as a non-$q\bar{q}$ meson.

However, the Obelix Collaboration at LEAR, analyzing $K^\pm K_S\pi^\mp$ at three hydrogen densities, reports this state at a much lower mass of 1290 MeV, with a very small width of 80 MeV [30]. The latter is unlikely for a $q\bar{q}$ scalar state. In fact they also report a second solution at 1480 MeV, with a width of 200 MeV, which agrees with Crystal Barrel but which is not favoured by their fit.

The isoscalar $f_0(1370)$ and $f_0(1500)$ mesons were established by Crystal Barrel, first in their $\eta\eta$ decay modes [31]. A sample of about 700,000 annihilations into $3\pi^0$ [26] and 200,000 annihilations into $\pi^0\eta\eta$ [32] confirmed the presence of both states decaying to $\pi^0\pi^0$ and $\eta\eta$. The $f_0(1370)$ is broad (~ 350 MeV) while $f_0(1500)$ is rather narrow (~ 100

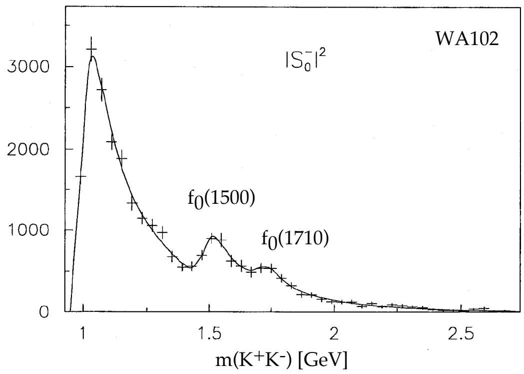

Figure 3. K^+K^- S-wave intensity in pp central production at 450 GeV. The line is the fit of partial wave amplitudes (from ref. [34]).

MeV). These two states were also observed by Crystal Barrel in their $K\bar{K}$ and $4\pi^0$ decay modes and $f_0(1500)$ in its $\eta\eta'$ mode [15]. Their $K\overline{K}$ decay rates are small compared to $\pi\pi$, indicating that neither can be dominantly $s\overline{s}$ [15]. The $f_0(1500)$ has been observed in many reactions and is now one of the best established unstable mesons [33].

The WA102 Collaboration at CERN observes the $f_0(1500)$ decaying to K^+K^-, K_SK_S, $\pi^+\pi^-$ and $\pi^0\pi^0$ in pp central production at 450 GeV [34]. Figure 3 shows the K^+K^- S-wave. The $\pi\pi$ mode appears to be favoured over $K\bar{K}$ [35]. Also, the $f_0(1370)$ is needed in $\pi\pi$, but not in $K\bar{K}$. This indicates that both $f_0(1370)$ and $f_0(1500)$ do not have large $s\bar{s}$ components, in agreement with Crystal Barrel results.

2.5. The $f_0(1710)$ meson

The spin of the $f_0(1710)$ meson was controversial ($J = 0$ or 2), some experiments even reporting both a $J^{PC} = 0^{++}$ and a 2^{++} state around 1700 MeV [1]. The issue has now hopefully been settled in favour of 0^{++} by the new data from WA102 [34]: a scalar state decaying to $K\overline{K}$ (see fig. 3) and $\pi\pi$ is reported around 1730 MeV.

A model was proposed in ref. [4] to explain the proliferation of scalar isoscalar states: the data from Crystal Barrel were consistent with a mainly $n\bar{n}$ state, $f_0(1370)$, with a small admixture of glue, while $f_0(1500)$ was mainly gluonic with a small contribution from $n\bar{n}$ and $s\bar{s}$. The mainly $s\bar{s}$ (with a small admixture of glue) was expected above 1600 MeV. Such a scalar state would decay mostly to kaonic channels. The branching fraction for $f_0(1710) \to K\bar{K}$ appears to be large compared to $\pi\pi$ [35]. Hence $f_0(1710)$ could be the expected (mainly $s\bar{s}$) scalar meson.

Two-photon processes are useful to probe the charge content of mesons through their electromagnetic couplings. Glueballs do not couple directly to photons and their production should therefore be suppressed in $\gamma\gamma$ processes. Apart from phase space factors one expects for the two isoscalar f' and f mesons the ratio of $\gamma\gamma$ widths

$$\frac{\Gamma_{\gamma\gamma}(f')}{\Gamma_{\gamma\gamma}(f)} = \left(\frac{\cos\theta - 2\sqrt{2}\sin\theta}{\sin\theta + 2\sqrt{2}\cos\theta}\right)^2 = \frac{2}{25} \tag{2}$$

for ideal mixing ($f' = s\bar{s}$ and $f = n\bar{n}$, nonet mixing angle $\theta = 35.3°$).

New data in $\gamma\gamma$ collisions have been presented by the LEP collaborations. L3 using untagged photons [36] observes three peaks below 2 GeV in the K_SK_S mass distribution (fig. 4). The lowest peak corresponds to $f_2(1270)$ and $a_2(1320)$, interfering destructively.

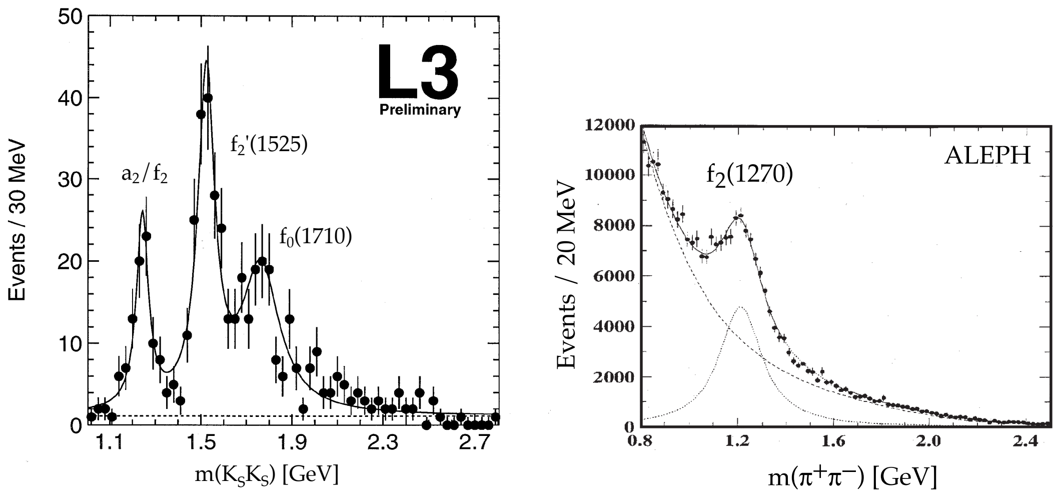

Figure 4. Left: $K_S K_S$ mass distribution in $\gamma\gamma$ collisions at LEP/L3, adapted from ref. [36]. Right: $\pi^+\pi^-$ mass distribution from LEP/ALEPH, from ref. [37].

The amplitude analysis leads to a tensor meson at 1525 MeV, $f_2'(1525)$, while $f_0(1500)$ is not needed. The third peak has mass 1765 $\pm$ 22 MeV and width 200 $\pm$ 50 MeV, but its spin (0 or 2) cannot be determined.

Since $f_0(1500)$ does not couple strongly to $K\bar{K}$ its absence in fig. 4 is not surprising. However, the ALEPH Collaboration studying the reaction $\gamma\gamma \to \pi^+\pi^-$ does not observe $f_0(1500)$ either (see fig. 4). Since $f_0(1500)$ has a large coupling to $\pi\pi$ this indicates that $f_0(1500)$ is not produced in $\gamma\gamma$ processes. This was to be expected if $f_0(1500)$ is mostly gluonic.

The high mass state in fig. 4 left is consistent with the $f_0(1710)$ observed by WA102. As an $n\bar{n}$ state it would generate a large $\pi\pi$ signal which ALEPH does not observe in $\gamma\gamma$. Hence the $K_S K_S$ signal in fig. 4 points to a large $s\bar{s}$ component for $f_0(1710)$, in accord with the WA102 data. The $\gamma\gamma$ width can be estimated from equ. (2) using 4 keV for a scalar $n\bar{n}$ mesons like $f_0(1370)$ [38]. One finds $\sim$ 0.3 keV for a mostly $s\bar{s}$ state, ignoring phase space and assuming that the $K\bar{K}$ decay mode is dominant. This is consistent with my own estimate from fig. 4 [33].

Note that in the limit of ideal mixing the OZI rule forbids the production of $s\bar{s}$ states in $p\bar{p}$ annihilations. Indeed, Crystal Barrel is not reporting any signal from $f_0(1710)$ [39]. Thus $f_0(1710)$ cannot have a large $n\bar{n}$ component.

The structure of the scalar meson nonet is therefore highly suggestive: it would consist of the broad isovector $a_0(1450)$, the broad $K_0^*(1430)$, the broad (mostly $n\bar{n}$) $f_0(1370)$ - which may or may not be different from the high energy tail of the σ - and the (mostly $s\bar{s}$) $f_0(1710)$. The narrow $f_0(1500)$ is an additional state composed mostly of glue. The amount of $q\bar{q}$ mixing with glue can be estimated once all data have been finalized. In this scenario the $a_0(980)$, $f_0(980)$, σ (and the controversial $\kappa \to K\pi$) are of a different nature, perhaps meson-meson resonances [27]. Note that alternative more complex mixing schemes have been proposed [40].

3. SEARCHING FOR THE 2^{++} GLUEBALL

The isoscalar $1^3P_2(2^{++})$ $q\overline{q}$ mesons, $f_2(1270)$ and $f_2'(1525)$, are well known. Above the $f_2'(1525)$ none of the nine reported isoscalars [1] can be definitely assigned to the 2^3P_2, 3^3P_2 or 1^3F_2 nonets. A systematic study of the two-body channels $\pi\pi$, $K\overline{K}$, $\eta\eta$ and $\eta\eta'$, similar to the one performed for scalar mesons at lower energy, would have to be conducted. Three to four states appear to be solid: (i) the $f_2(1565)$ (or AX) observed at LEAR in $\overline{p}p$ annihilation at rest is perhaps the same state as $f_2(1640)$ also reported to decay into $\omega\omega$ (for references see the meson listings [1]); (ii) the rather broad $f_2(1950)$ decaying to 4π and $\eta\eta$ [39] is observed by several experiments; (iii) a broad structure (of perhaps several states) decaying to $\phi\phi$ was reported around 2300 MeV. We discuss first the evidence for a narrow structure around 2230 MeV.

3.1. The f$_J$(2230) meson (or ξ)

The evidence for a $\sim$ 20 MeV broad state around 2230 MeV dates back to Mark III at SPEAR. It was seen in radiative J/ψ decay to K^+K^- and K_SK_S [41]. The latter implied that J^{PC} = (even)$^{++}$. This state was reported recently by BES at the e^+e^- collider in Beijing. Its mass is 2231.1 $\pm$ 3.5 MeV and its width $23\pm^{8}_{7}$ MeV [1] and it was observed by BES to decay into $\pi^+\pi^-$, K^+K^-, K_SK_S, $\overline{p}p$ [42] and $\pi^0\pi^0$ [43] with a significance of about 4σ in each decay mode. Several features make this state an attractive candidate for the 2^{++} glueball: (i) its mass which agrees with lattice predictions (although the 2^{++} assignment has not really been proven); (ii) its unusually narrow width assuming it were a $q\overline{q}$ excitation; (iii) its observation in the gluon rich environment of J/ψ radiative decay; (iv) its comparable partial widths to $\pi\pi$ and $K\overline{K}$, in line with flavour independence; (v) its non-observation in $\gamma\gamma$ collisions [44].

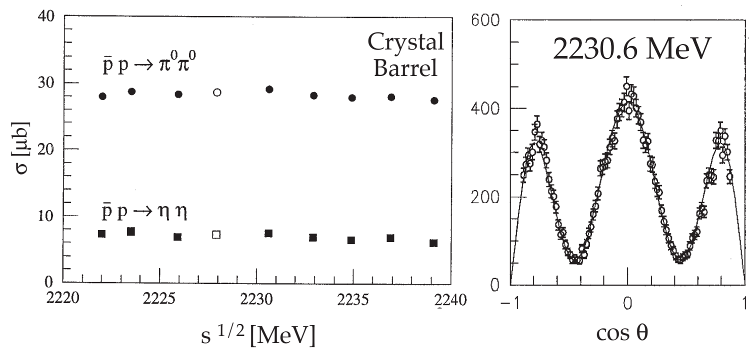

Figure 5. (a) Cross section for $\overline{p}p \to 2\pi^0$ and 2η (for cos$\theta < 0.7$); (b) $\pi^0\pi^0$ angular distribution at 2230.6 MeV. Plotted is the emission angle of one of the 2γ systems consistent with the decay of a π^0. The curves are fits with Legendre polynomials up to ℓ=8 (from ref. [45]).

If ξ decays to $\overline{p}p$ then it should also be observable in $\overline{p}p$ formation experiments. However, all searches in $\overline{p}p \to \xi \to 2\pi$, $K\overline{K}$ and $\phi\phi$ have been negative. Crystal Barrel has searched for narrow states decaying to $\pi^0\pi^0$ and $\eta\eta$ (leading to 4γ) as a function of $\overline{p}$ momentum. Figure 5a shows the cross sections for nine momenta in the mass range of the ξ. The resolution was about $\pm$ 0.6 MeV in the c.m.s. system thanks to the very good resolution of the LEAR beam and the small target size. Figure 5b shows the angular distribution for $\pi^0\pi^0$ in the c.m.s system which does not vary significantly with $\overline{p}$ momentum. No structure is observed. Using the product of branching fractions $B(J/\psi \to \gamma\xi)B(\xi \to \overline{p}p, \pi^0\pi^0)$ measured by BES and the typical upper limit of 4×10^{-5} for $B(\overline{p}p \to \xi)B(\xi \to \pi^0\pi^0)$ measured by Crystal Barrel, one finds that the observed decays amount to at most 4% of all ξ decays, hence most ξ decay channels have not been observed yet. Furthermore, $B(J/\psi \to \gamma\xi) > 5 \times 10^{-3}$ which is comparable to the branching ratio for the known decay $J/\psi \to \gamma\eta'$. However, a striking η' is observed in the inclusive J/ψ decay spectrum, while ξ is not [46]. Hence the data are inconsistent: the $\overline{p}p$ decay width measured at BES appears to be too large or the *narrow* ξ simply does not exist.

However, the JETSET Collaboration at LEAR measuring the cross section for $\overline{p}p \to \phi\phi \to K^+K^-$ reports a broad enhancement at 2.2 GeV, just above the $\phi\phi$ threshold [47]. This channel should be suppressed by the OZI rule. A partial wave analysis was performed [48]: the dominating contribution was 2^{++} with a resonant contribution from the D_0 amplitude (antiparallel ϕ spins) with mass 2231 $\pm$ 2 and width 70 $\pm$ 10 MeV, corresponding to a *broad* ξ meson. The author of ref. [48] argues that decay widths of the isoscalar $s\overline{s}$ mesons (e.g. 1^3F_2) should be small near the $\phi\phi$ threshold and that the large $\phi\phi$ cross section could be due to the production of the 2^{++} glueball. Rescattering via triangular K-exchange in $\overline{p}p \to K\overline{K} \to \phi\phi$ was estimated to be two orders of magnitude below the measured signal [49]. Similar $\phi\phi$ enhancements were reported earlier in this mass range in $\pi^-p \to \phi\phi n$ [50].

3.2. SEARCH FOR 1^{-+} HYBRIDS

A 1^{-+} exotic meson with a mass of 1370 MeV and a width of 385 MeV was reported with 18 GeV pions in $\pi^-p \to \eta\pi^-p$ at the MPS in Brookhaven [51]. It was observed as an interference between the $\eta\pi$ $L = 1$ and $L = 2$ $a_2(1320) \to \eta\pi$ amplitudes, leading to a forward/backward asymmetry in the $\eta\pi$ angular distribution.

Crystal Barrel has searched for a resonance in the $\eta\pi$ P-wave with $\overline{p}n \to \pi^-\pi^0\eta$ in liquid deuterium at rest [52]. The Dalitz plot is shown in fig. 6. Conspicuous is the strong production of ρ^- and the accumulation of events in the $\eta\pi$ mass regions around 1400 MeV but only above the ρ band. This points to the presence of interferences between $a_2(1320)$ and some other amplitude: The partial wave analysis required the inclusion of a resonant 1^{-+} P-wave with mass 1400 and width 310 MeV, in agreement with ref. [51]. This state was also observed in the annihilation channel $\overline{p}p \to \pi^0\pi^0\eta$ [53].

Another 1^{-+} state at 1593 MeV with a width of 168 MeV and decaying into $\rho\pi$ was also reported at the MPS in the reaction $\pi^-p \to \pi^-\rho^0 n$ at 18 GeV [54]. It was also observed in $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$ (but not $\eta\pi$) by the VES Collaboration at Serpukhov [55].

Hence we now have two good 1^{-+} exotics, $\pi_1(1400)$ and $\pi_1(1600)$. A recent publication suggests that $\pi_1(1400)$ does not exist but is actually the result of an interference between $\pi_1(1600) \to b_1(1235)\pi \to \eta\pi$ and the Deck generated $\eta\pi$ background [56]. However, a

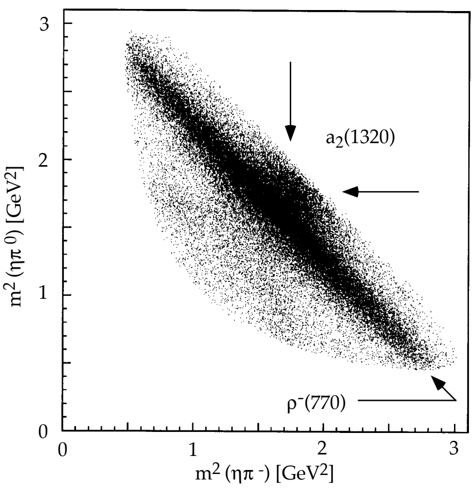

Figure 6. Dalitz plot of $\overline{p}n \rightarrow \pi^-\pi^0\eta$ from Crystal Barrel (52,576 events, from ref. [52]).

state at 1600 MeV decaying to $\eta\pi$ cannot be accommodated by Crystal Barrel data [57].

As isovectors, $\pi_1(1400)$ and $\pi_1(1600)$ cannot be glueballs. The coupling to $\eta\pi$ of the former points to a four-quark state while the strong $\eta'\pi$ coupling of the latter is favoured for hybrid states [58]. Its mass is not far below the lattice prediction [7].

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