Observation of Two $J^{PC} = 0^{++}$ Isoscalar Resonances at 1365 and 1520 MeV

The CRYSTAL BARREL Collaboration

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1 Abstract

From a simultaneous analysis of data on $\overline{p}p \to \pi^0\pi^0\pi^0$ and $\overline{p}p \to \eta\eta\pi^0$ at rest, two $I = 0$ $J^{PC} = 0^{++}$ resonances are identified above 1 GeV. The first has mass $M = 1365^{+20}_{-55}$ MeV and width $\Gamma = 268 \pm 70$ MeV, close to the $f_0(1400)$ of the Particle Data Group. The second has $M = 1520 \pm 25$ MeV, $\Gamma = 148^{+20}_{-25}$ MeV.

2 Text

Mesons in the $J^{PC} = 0^{++}$ sector have until now been shrouded in uncertainty. We report an amplitude analysis throwing new light on the situation up to 1.6 GeV. The information comes from an analysis of $\overline{p}p$ annihilation at rest into the channels $\pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$. These data were obtained by stopping antiprotons from the CERN Low Energy Antiproton Ring (LEAR) in the liquid hydrogen target of the Crystal Barrel detector [1].

In our earlier publications [2, 3], the two channels were analysed separately. Here both are fitted simultaneously with a consistent set of resonance parameters. The $I = 0$ $J^{PC} = 0^{++}$ partial wave in the $\eta\eta\pi^0$ data was found in Ref. [2] to require two resonances decaying to $\eta\eta$. The first was at 1430 MeV with a width of 250 MeV, and the second at 1560 ± 25 MeV, with a width of 245 ± 50 MeV. Annihilation occurred largely from the initial state ${}^1S_0$, with 12% from ${}^3P_1$. In [3], the scalar $\pi^0\pi^0$ partial wave of the $\pi^0\pi^0\pi^0$ data above 1.1 GeV contained only one pole, interpreted as the $f_0(1400)$, and the region around 1500 MeV was fitted with an $I = 0$ $J^{PC} = 2^{++}$ resonance at 1515 ± 10 MeV with a width of 120 ± 10 MeV. However, the fit required 60% of the annihilation to stem from initial ${}^3P_1$ and ${}^3P_2$ states, a surprising result as most $\overline{p}p$ annihilation channels at rest in liquid hydrogen show a large initial S-wave dominance.

Here we present an alternative interpretation where both $\pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$ channels are fitted assuming pure ${}^1S_0$ annihilation. This fit requires two 0^{++} resonances at 1365 and 1520 MeV. The change in the fit is very largely in $\pi^0\pi^0\pi^0$, so we concentrate on a discussion of this channel. With the restriction to a single initial state, interference between the three pairs of particles in the final state determines the $\pi\pi$ and $\eta\eta$ amplitudes with great phase sensitivity.

The $3\pi^0$ data are shown in Fig. 1. Because of the identity of the three pions, the plot has sixfold symmetry. We choose to discuss the top left corner. The new interpretation rests upon resolving the structure previously ascribed to a single

$A_X(1515)$ into two components. The first of these, which we call A, is a narrow band at $s_{12} \simeq 2.3\ GeV^2$ running the full width of the corner of the Dalitz plot. We shall show that this is due to a 0^{++} resonance. There is a second broad feature peaking near the middle of the band, but centred at slightly higher mass $s_{12} \simeq 2.5\ GeV^2$, $s_{23} \simeq 0.6\ GeV^2$. This latter bump, which we call B, can be fitted dominantly by constructive interference between two broad enhancements centred at $s_{23} = s_{13} = 0.6\ GeV^2$. Here the $\pi\pi$ S- wave phase shift δ_S is known from previous work of Au, Morgan and Pennington [4] to rise slowly through 90° over a wide mass range, 600 to 950 MeV. This is the old σ resonance.

Figure 2 shows the amplitude squared for the $\pi\pi \rightarrow \pi\pi$ S-wave. In order to constrain the fit to bump B as tightly as possible, we fit simultaneously the annihilation data and the $\pi\pi \rightarrow \pi\pi$ amplitude. For the latter, we have gone back to the original data sources from $\pi N \rightarrow \pi\pi N$ [5] and K_{e4} decay [6]. The formalism is given in full below, but first we outline the physics.

Consider first the bump B of Fig. 1. At $\cos\theta_{13} = 0$, the two σ bands are in phase, and create a peak centred at about 1560 MeV. As one moves along a line of fixed s_{12} to lower s_{23}, the phase of the $\pi\pi$ S-wave amplitude in channel 23 decreases, but s_{13} increases and with it the phase of the amplitude in channel 13. On either side of $\cos\theta_{12} = 0$, these two amplitudes become out of phase with one another and the intensity falls, creating bump B. Fig. 3 shows slices of the Dalitz plot at a series of values of s_{12}. The central bump has a width in terms of $(s_{23} - s_{13})$ which is independent of s_{12}. The flat component A peaks at $\sqrt{s_{12}} = 1520$ MeV, the central bump at 1560 MeV. The fit requires that these two components interfere with one another and also with the tail of $f_2(1270)$. This point illustrates two important features of the present approach. Firstly, it shows that all three interfering amplitudes may originate coherently from a single $p\overline{p}$ initial state, which we now take to be ${}^1S_0$. Secondly, the fit shows that the band at $s_{12} = 2.3\ GeV^2$ indeed has the phase variation of a narrow resonance.

The Argand diagrams we obtain for the $\pi\pi$ S-wave amplitudes in $p\overline{p} \rightarrow 3\pi^0$ and $\eta\eta\pi^0$ are shown in Fig. 4. For $3\pi^0$, there is a broad loop due to δ_S going through 90° at 800 MeV, followed by a small loop due to $f_0(975)$, then a complicated structure due to $f_0(1365)$ and $f_0(1520)$. The dip in intensity at masses between $f_0(1365)$ and $f_0(1520)$ is visible in the $3\pi^0$ data of Fig. 1, though obscured by $f_2(1270)$. It is also clearly visible in the $\eta\eta\pi^0$ data of Ref. [2] (Fig. 2 there, and Fig. 5 here).

We now give the explicit algebraic forms used to fit the $\pi\pi$ S-wave and the $p\overline{p}$ data. We fit the former using the two channel approach of Au, Morgan and

Pennington[4] with $\pi\pi$ as channel 1 and $\overline{K}K$ as channel 2. It is the part up to 1.1 GeV which is important; above this energy, the CERN-Munich data have indicated only a slowly varying phase. The scattering amplitude can be written in terms of a 2×2 $K-$ matrix $\hat{K}$ as follows:

$$\hat{T} = \hat{K}(I - i\hat{\rho}\hat{K})^{-1} \tag{1}$$

and so for $\pi\pi \to \pi\pi$

$$\begin{aligned} T_{11} &= \frac{K_{11} - i\rho_2(K_{11}K_{22} - K_{12}K_{21})}{D} && (2) \\ D &= 1 - i\rho_1 K_{11} - i\rho_2 K_{22} - \rho_1\rho_2(K_{11}K_{22} - K_{12}K_{21}) && (3) \end{aligned}$$

where

$$\begin{aligned} \rho_1 &= (1 - 4m_\pi^2/s)^{1/2}, \qquad m_\pi = 134.96\ MeV && (4) \\ \rho_2 &= (1 - 4m_K^2/s)^{1/2}\ for\ s > 4m_K^2, \qquad m_K = 495.67\ MeV && (5) \\ &= +i(4m_K^2/s - 1)^{1/2}\ for\ s < 4m_K^2. && (6) \end{aligned}$$

The matrix elements K_{ij} are parametrised by:

$$K_{ij} = \left(\frac{s - 2m_\pi^2}{s}\right)\left(\frac{\alpha_i\alpha_j}{s_A - s} + \frac{\beta_i\beta_j}{s_B - s} + \frac{\gamma_i\gamma_j}{s_C - s} + A_{ij} + B_{ij}s\right). \tag{7}$$

The processes of three-meson production involve a sum of diagrams with final state interactions of outgoing particles. The low energy part of the two-pion S-wave interaction in the final state for particles $(\alpha\beta)$ can be written $T = N_{\pi\pi}(s_{\alpha\beta})/D(s_{\alpha\beta})$, where the denominator is identical to that used to fit the low energy part of δ_S, while the numerator is related to the three-meson production amplitude and will in general be modified from that fitting δ_S. This is the essential point of difference from previous attempts to fit these data. In [3], $N(s)$ was taken to be identical to that of $\pi\pi$ elastic scattering. We depart from this restrictive assumption by taking

$$N_{\pi\pi}(s_{\alpha\beta}) = (\Lambda_1 + \Lambda_2 s_{\alpha\beta})K_{11} + i\rho_2(\Lambda_3 + \Lambda_4 s_{\alpha\beta})(K_{11}K_{22} - K_{12}K_{21}). \tag{8}$$

The same form is assumed for $N_{\eta\eta}$, except that Λ_2 and Λ_4 are set to zero, because of the limited mass range involved. Note, that here the K-matrix elements in $N(s)$ do not have the same meaning as in the two-channel approach of [4], but form, together with the first order polynomials in s, a convenient parametrisation, flexible enough to account for the s-dependence of three-meson production. We have checked that the fit results are rather insensitive to a great variety of modifications in the parametrisation of $N(s)$. Triangle diagrams involve final state particles emerging from one resonance and rescattering through a second resonance with the spectator. These diagrams make the Λ_i parameters complex in general, although in practice the values we fit to Λ_2, Λ_3 and Λ_4 have phases not far different from that of Λ_1. A full account of this method will be presented elsewhere [7].

Above 1.1 GeV, further resonances demanded by the $\overline{p}p$ data are described by additional terms

$$T(s) = \frac{\Lambda B_J/B_{Jr}}{s - M^2 + iM\Gamma D_J/D_{Jr}} \tag{9}$$

where $\Gamma = g\rho_1$, with g a constant and ρ_1 given by (4). For the centrifugal barrier in the case of the production of D-wave resonances we use:

$$\begin{aligned} B_2(s) &= \frac{p^2q^2(3\cos^2\theta - 1)/2}{[p^2(p^2+X_2)+X_2^2]^{1/2}[q^2(q^2+X_2)+X_2^2]^{1/2}}, & (10)\\ X_2 &= 0.356\ GeV^2. & (11)\end{aligned}$$

Here B_{Jr} is the value, on resonance, $B_J(M^2)$ for $\cos\theta = 1$; $q(s)$ is the momentum of decay products of the resonance in its rest system, $p(s)$ is the momentum of the resonance in the overall centre of mass system and θ is the angle between these momenta. The value of X_2 has been determined to fit best the $f_2(1270)$ in the $\pi^0\pi^0\pi^0$ data of [3]. Centrifugal barriers are likewise included by a mass-dependent width in Eq. (9) for the decay of $J = 2$ resonances, where $D_{Jr} = D_J(M^2)$ and

$$D_2(s) = \frac{q^4}{q^2(q^2+X_2)+X_2^2}. \tag{12}$$

We have not explicitly included the $\pi\pi$ $I = 2$ S-wave. It is almost a constant amplitude over the mass range of interest and cannot be separated from the slowly varying component of the $I = 0$ S-wave.

In this approach, the $\pi\pi$ S-wave amplitude in annihilation reactions is described by the superposition of two components, one originating from the $\pi\pi$ phase shifts parametrised as N/D, the second from two resonances demanded by the $\overline{p}p$ data. This is forced upon us by the fact that the CERN-Munich data do not resolve these two resonances. Therefore, we have determined beforehand the parameters of the K-matrix elements (7) in a simultaneous fit to the CERN-Munich data and to the $3\pi^0$ data discussed here. The CERN-Munich data were described by T_{11} from Eq. (2), and for the annihilation data the $\pi\pi$ S-wave was parametrized by the N/D term and Breit-Wigner resonances. These K-matrix parameters (Table 1) are then used as fixed input values in the simultaneous fit to $\overline{p}p \to 3\pi^0$ and $\overline{p}p \to \eta\eta\pi^0$ data. These data require, in addition to the N/D term, two Breit-Wigner resonances at 1365 - 134i MeV and 1520 - 74i MeV, respectively. The denominator D, common to all descriptions, has T-matrix poles at 970 - 56i MeV, 1071 - 290i MeV and 1548 -183i MeV.

Below 1 GeV, $f_0(1365)$ and $f_0(1520)$ contribute amplitudes which are almost constant. Above 1 GeV, these resonances describe the structures observed in the annihilation data, while the amplitude from the N/D piece contributes a slowly varying featureless component, which is essentially a blurred combination of $f_0(1365)$ and $f_0(1520)$. Additional evidence that the pole due to the N/D term at 1548 - 183i MeV has no large systematic influence on the parameters of the $f_0(1365)$ and $f_0(1520)$ stems from the fact that the Argand plots (Fig. 4), corresponding to the fit of the $\overline{p}p$ Dalitz plots, can themselves be fitted extremely well above 1.2 GeV by the combination of exactly two Breit-Wigner resonances, located at 1365 - i146 MeV and 1499 - i82 MeV, respectively, and a parabolic background in s. Other fitting functions for Eqs. (7), (8) have been tried, all leading to similar Argand plots with the two Breit-Wigners in the vicinity of 1365 and 1520 MeV. We therefore conclude that the T-matrix pole at 1548 - 183i MeV, contained in the N/D term, in fact duplicates some of the contribution of two 0^{++} resonances to the $\pi\pi$ S-wave in this mass region. The two resonances are more clearly visible in $\overline{p}p$ data than in CERN-Munich data because the centrifugal barrier inhibits access to states of high angular momentum J in annihilation at rest.

In addition, we have clear evidence that these two scalar resonances, $f_0(1365)$ and $f_0(1520)$, have a large inelasticity and appear therefore in $\pi\pi$ elastic scattering only as weak features, so far unresolved. The $f_0(1520) \rightarrow \eta\eta$ provides the second largest contribution to the $\eta\eta\pi^0$ annihilation channel; we estimate its $\eta\eta : \pi\pi$ branching ratio to be of the order $1:5$. Moreover, our collaboration has observed in $\overline{p}p \rightarrow 5\pi$ strong production of a 0^{++} resonance decaying into 4π, mostly $\rho\rho$, with $M = 1374 \pm 38$ MeV and $\Gamma = 375 \pm 61$ MeV [8]. It is natural to assume that we are observing here the 4π decay of the $f_0(1365)$. The ratio of the decays into 4π and 2π, not very accurately determined, is of the order 5. We should note that previous observations of scalar mesons decaying to 4π and $\overline{K}K$ have been reported, in particular by the Obelix Collaboration [9] and the WA76 Collaboration [10].

Parameters of the fit to $\pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$ are given in Table 2. Projections onto the axes of the Dalitz plots, shown in Fig. 5, illustrate the quality of the fit. The analysis is stable under the forced introduction of up to 15% initial P-states in either or both channels. In fitting $\eta\eta\pi^0$ data, the $a_0(980)$ is fitted with a Flatté form [11], with the $\overline{K}K/\eta\pi$ branching ratio taken from the average value of Lockman [12].

The errors on the resonance parameters listed in Table 2 are not statistical, but systematic. They are upper limits spanning all variations observed in several hundred fits with different parametrisations. The mass and width of the $f_2(1270)$ have been introduced as fixed quantities in the fit. The mass and width of $f_2'(1525)$ have been fixed to the values of the Particle Data Tables [13].

The χ^2 of the fit to $\pi\pi$ data of Refs. [5] and [6] is 1.1 per degree of freedom. It is 1.5 for the channel $\pi^0\pi^0\pi^0$ (one sextant of the Dalitz plot being divided into 229 bins) and 1.1 for the $\eta\eta\pi^0$ (321 bins). The number of fitted parameters is 20 for $\pi^0\pi^0\pi^0$ and 12 for $\eta\eta\pi^0$. For $f_0(1520)$, the identification $J = 0$ is conclusive in both $\pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$. In the case of $\pi^0\pi^0\pi^0$, χ^2 rises by over a factor 5 if J is chosen as 2 instead of 0; for $\eta\eta\pi^0$, χ^2 doubles. Likewise, $f_0(1365)$ is required in both data sets: fits with only a single resonance increase χ^2 from 697 to 2063. Without either resonance, χ^2 rises to 9522.

The changes of mass and width obtained in this fit for the $f_0(1520)$ from those obtained in the previous analysis of the $\eta\eta\pi^0$ channel [2] are due to the additional constraints imposed here by the simultaneous fit of the $3\pi^0$ and $\eta\eta\pi^0$ channels. They also arise in part from the use of the Flatté form for $a_0(980)$ in place of the Breit-Wigner amplitude used in [2]. This is demonstrated by the fact that free fits to individual channels can yield very similar masses and widths for the $f_0(1365)$ and the $f_0(1520)$. Note that the Flatté parameters obtained here (see Table 2) should not be identified with the $a_0(980)$ parameters given in the Particle Data Tables [13]. A more accurate determination of the $a_0(980)$ parameters will be given elsewhere [14].

In addition to the $f_0(1520)$, the $\eta\eta\pi^0$ data require as well a small contribution from $f_2(1270)$ and $f_2'(1525)$ (see Table 2). One may also accomodate a small contribution of $G/f_0(1590) \to \eta\eta$ (about 10 % of the $f_0(1520)$ contribution), the mass and width of the resonance being fixed to the Particle Data Table values [13]: (m = 1587 MeV, Γ = 175 MeV) but, with the present statistics, this contribution is not significant ($\Delta\chi^2 = 11$).

In the $3\pi^0$ data, it is necessary to include an additional $J = 2$ amplitude above the mass of $f_2(1270)$. This amplitude is denoted D in Table 2. It has the effect of reducing χ^2 for the $3\pi^0$ fit by a factor 1.5. There is, therefore, no doubt of its presence. Its role is not in fitting the central bump, but the edges of the Dalitz plot near $\cos\theta = \pm 1$. Attempts to eliminate it by a more complicated $N(s)$ for the $\pi\pi$ S-wave have not been successful, so it truly seems to represent a small additional

D-wave effect. It may be associated with the $\rho\rho$ threshold. Other possible sources are $f_2(1430)$, $f_2(1520)$ (the Ax(1515) of [3]), $f_2(1640)$ and $f_2(1810)$ or even the $\Theta(1710)$ with $J = 2$. Contributions from the higher mass resonances are shifted downwards in energy by the effect of the $L = 2$ centrifugal barrier for production from the initial ${}^1S_0$ state. None individually gives an optimum fit with mass and width taken from the Particle Data Tables[13]. The best mass and width are not far from those attributed to the $AX/f_2(1515)$ in [3], but in that work it arose mainly from initial $\overline{p}p$ P-states, while here our analysis assumes pure ${}^1S_0$ initial states.

As an additional check, we have also made a fit to data taken by the Asterix collaboration [15] on P-state annihilation to $\pi^+\pi^-\pi^0$, obtained using an L X-ray in coincidence. This channel has the same initial P-states as $3\pi^0$, but in addition ${}^1P_1$ annihilation. Our fit to the Asterix data, ($\chi^2 = 1.40$ per point), fits the A_X peak triple interference between $f_0(1520)$ and two crossing $\rho(770)$ bands, originating from the ${}^3P_1$ initial state. This shows that our present solution is compatible with Asterix data.

One motivation in Ref. [3] for fitting with P-state annihilation was that ${}^3P_2$ leads naturally to a zero at the centre of the Dalitz plot, in agreement with Fig. 1. However, this dip may have a different, dynamical origin. Kalogeropoulos et al.[16] studied the related channel $\overline{p}n \rightarrow \pi^-\pi^+\pi^-$ at a number of $\overline{p}$ momenta. Their data, notably their Fig. 20, shows a regular lattice of peaks and dips, which many authors have sought to explain with dual models. The dip which appears at the centre of Fig. 1 seems to be at fixed t in Ref. [16] , suggesting it is of dynamic origin, rather than a signature of P-state annihilation. Our Λ parameters in $N(s)$ generate maxima at low and high s (see Fig. 4) and a dip at $s = 1$ GeV^2, which is further accentuated by destructive interference with the $f_2(1270)$.

The apparent ambiguity in the interpretation of the three-pseudoscalar final states $3\pi^0$ and $\eta\eta\pi^0$ (S/P ratio, rates of production, resonance decay mode) will be the subject of further studies by the Crystal Barrel Collaboration. In this vein, the use of high statistics data samples will allow for a much finer resolution in the Dalitz plot. Additionally, the inclusion of a larger number of final states in the coupled channel analysis will therein provide additional constraints. Finally, the accumulation of data with the use of a gas hydrogen target, thereby changing the S/P fraction of the initial state, will help to resolve this ambiguity. It should be emphasized, nonetheless, that the main conclusion of the present letter, the existence of two I=0 scalar mesons, the $f_0(1365)$ and the $f_0(1520)$, is not affected by such an ambiguity.

We now turn briefly to the interpretation of $f_0(1365)$ and $f_0(1520)$. It is natural to associate $f_0(1365)$ with a $(u\overline{u}+d\overline{d})$ state in the same nonet as $K_0^*(1430)$. Elsewhere we report evidence for an $I=1$ $J^P=0^{++}$ resonance at about 1450 MeV [14]. Could we then assign $f_0(1520)$ to the ninth member of the 0^{++} nonet, mostly $s\overline{s}$? The LASS group claims to have observed a weak $f_0(1525)\rightarrow K_S^0K_S^0$ with $\Gamma=90$ MeV [17]; this might be identified with $f_0(1520)$. But this assignment raises problems because of the strong coupling we observe to $\pi\pi$. In fact, the branching ratios we obtain for $\pi\pi$ and $\eta\eta$ are close to those expected for $u\overline{u}+d\overline{d}$. Suppose $f_0(1520)$ were a normal $u\overline{u}+d\overline{d}$ state. Using the published mixing angle Θ_{PS} for the π, η, η' nonet [18],

$$\eta = 0.8(u\overline{u}+d\overline{d})/\sqrt{2} - 0.6s\overline{s} \tag{13}$$

and allowing a phase-space factor k for decay of $f_0(1520)$, the overlap with final $\eta\eta$ and $\pi\pi$ states is in the ratio 0.29, reasonably close to that observed.

Could $f_0(1520)$ be a molecule associated with $\omega\omega$ and/or $\rho\rho$ thresholds? This seems unlikely. It does not appear to couple to $\omega\omega$, and it seems much too narrow to be due directly to the $\rho\rho$ threshold. We have tried giving $f_0(1520)$ a width for coupling to $\omega\omega$. The data reject this firmly. On the Dalitz plots, no feature is apparent at the $\omega\omega$ threshold. Secondly, the E760 Collaboration has presented data [19] on $p\overline{p}\rightarrow\pi^0\pi^0\pi^0$, $\eta\eta\pi^0$ and $\eta\pi^0\pi^0$ from $p\overline{p}$ annihilation around 3 GeV. They observe a striking peak around 1500 MeV, both in $\pi^0\pi^0$ and $\eta\eta$ with $\Gamma\simeq 105$ MeV (J not determined). If this is the $f_0(1520)$, it is further evidence against a molecular interpretation: a molecular state will have a large radius and is unlikely to be produced strongly at 3 GeV because of form factors.

A clear possibility is that $f_0(1520)$ is the long awaited 0^{++} glueball, strongly mixed with $q\overline{q}$ in order to explain its predominant decay to $(u\overline{u}+d\overline{d})$ rather than $s\overline{s}$. We draw attention to DM2 and Mark III data on $J/\psi\rightarrow\gamma\rho\rho$ [20], which show a sharp peak compatible in mass and width with $f_0(1520)$. The snag is that both groups assign this peak quantum numbers $J^P=0^-$. However we note that their analysis has assumed the absence of $\sigma\sigma$ final states.

The $G/f_0(1590)$ observed by GAMS [21] has also been presented as a good candidate for the 0^{++} glueball ground state in view of its large $\eta\eta$ and even larger $\eta\eta'$ coupling. It is possible that the $f_0(1520)$ and $f_0(1590)$ are mixed states of a glueball and the ninth member of the $\overline{q}q$ nonet.

In summary, we find two resonances $f_0(1365)$ and $f_0(1520)$ as a result of a simultaneous fit to $\pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$. Both channels are consistent in masses and widths for these two states. The data are consistent with pure S-wave annihilation.

It is a mystery that $f_0(1520)$ couples so strongly to $\pi\pi$ if it is the ninth member of a nonet. It seems too narrow to be due directly to the $\rho\rho$ threshold, though it is quite likely that this threshold exerts some influence on the dynamics. The most interesting possibility is that it is a glueball, strongly mixed with $q\overline{q}$.

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Fig. 1. Dalitz plot for $\overline{p}p \to 3\pi^0$ at rest, from Ref. 2

Fig. 2 $|T_{11}|^2$, the $\pi\pi$ S-wave elastic scattering intensity.

Fig. 3 Slices through the Dalitz plot for fixed s_{12} and the corresponding fit.

Fig. 4. The Argand diagrams of the $\pi\pi$ S-wave contribution to (a) $\overline{p}p \to 3\pi^0$, (b) $p\overline{p} \to \eta\eta\pi^0$. The scale is arbitrary. Masses are marked in GeV by arrows.

Fig. 5. Projections of (a) $\pi^0\pi^0\pi^0$ data (histogram) onto $M^2(\pi^0\pi^0)$, (b) $\eta\eta\pi^0$ data onto $M^2(\eta\eta)$, compared with the fit.

Table 1: K-matrix parameters fitted to $3\pi^0$, $\eta\pi^0\pi^0$ and CERN-Munich phase-shift data. Units are GeV.

$\pi\pi \to \pi\pi$	$s_A = 0.7239$	$\alpha_1 = 0.6941$	$\alpha_2 = 0$
	$s_B = 1.5279$	$\beta_1 = 0.8974$	$\beta_2 = 0.0049$
	$s_C = 3.9657$	$\gamma_1 = 1.6385$	$\gamma_2 = -2.1499$
	$A_{11} = -0.2905$	$A_{12} = 2.0219$	$A_{22} = -0.4376$
	$B_{11} = -0.2049$	$B_{12} = 0$	$B_{22} = 0$

Table 2: Parameters fitted to $3\pi^0$ and $\eta\eta\pi^0$ data. Units are GeV. We have given the Λ parameters without errors, since they cannot be used for the precise extraction of branching ratios for the different resonances, due to the overlap of the N/D and Breit-Wigner terms. Other parameters without error have been fixed in the fit. The errors on resonance parameters are systematic and cover the entire range of fits made with different algebraic forms for the amplitudes.

Amplitude	M	Γ	$\Lambda_{\pi\pi}$	$\Lambda_{\eta\eta}$
$f_0(1365)$	$1.365\ ^{+0.020}_{-0.055}$	0.268 ± 0.070	1.729 - i0.160	-0.049 -i0.537
$f_0(1520)$	1.520 ± 0.025	$0.148\ ^{+0.020}_{-0.025}$	0.370 - i0.659	0.160 - i0.827
$f_2(1270)$	1.275	0.195	1.0	-0.348 + i0.673
f_D	$1.566\ ^{+0.080}_{-0.050}$	$0.166\ ^{+0.080}_{-0.020}$	0.417 + i0.483	
$f_2'(1525)$	1.525	0.076		0.078 - i0.234
$a_0(980)$	$1.024\ ^{+0.005}_{-0.026}$	$g_{\eta\pi} = 0.338^{+0.015}_{-0.090}$	$g_{KK}/g_{\eta\pi} = 1.337$	$\Lambda_{\eta\pi} = 1.0$
$\pi\pi$ S-wave	$\Lambda_1 = 0.2866 + i5.676$	$\Lambda_2 = -0.5465 - i5.552$		
	$\Lambda_3 = -0.7474 - i2.916$	$\Lambda_4 = 0.925 + i2.259$		
$\eta\eta$ S-wave	$\Lambda_1 = 5.208 + i5.987$	$\Lambda_3 = -2.772 + i3.731$		