Evidence for Two Isospin Zero $J^{PC} = 2^{-+}$ Mesons at 1645 and 1875 MeV

The CRYSTAL BARREL Collaboration

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Abstract

Crystal Barrel data on $\bar{p}p \to \eta\pi^0\pi^0\pi^0$ at beam momenta of 1.94 and 1.2 GeV/c reveal evidence for two $I = 0$ $J^{PC} = 2^{-+}$ resonances in $\eta\pi\pi$. The first, at $1645 \pm 14(stat.) \pm 15(syst.)$ MeV with width $180\ ^{+40}_{-21} \pm 25$ MeV, decays to $a_2(1320)\pi$ with $L = 0$. It may be interpreted as the $q\bar{q}\ ^1D_2$ partner of $\pi_2(1670)$. A strong signal is also observed just above threshold in $f_2(1270)\eta$ with $L = 0$. It is 10–20 times stronger than is expected for the high mass tail of the 1645 MeV resonance. It can be fitted as a second 2^{-+} resonance at $1875 \pm 20 \pm 35$ MeV with width $200 \pm 25 \pm 45$ MeV. A third 2^{++} resonance at $2135 \pm 20 \pm 45$ MeV with $\Gamma = 250 \pm 25 \pm 45$ MeV, decaying to both $a_2(1320)\pi$ and $f_2(1270)\eta$ with $L = 1$, is compatible in mass and width with $f_2(2175)$ observed earlier by the GAMS group.

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An isospin $I = 0$ $^1D_2$ $q\bar{q}$ resonance is expected in the vicinity of 1650-1700 MeV. Also, in the cavity model of glueballs proposed by Jaffe and Johnston [1], a 2^{-+} state is predicted. These missing states have prompted us to study $\eta\pi\pi$ states in $\bar{p}p \to (\eta\pi^0\pi^0)\pi^0$. The data were taken with the Crystal Barrel detector using $\bar{p}$ beams of 1.94 and 1.2 GeV/c from LEAR. This paper will concern mostly the data at 1.94 GeV/c. Those at the lower momentum show similar but weaker features and will be reported separately, except for one important detail bearing on the interpretation of the data at 1.94 GeV/c.

The detector has been described in detail earlier [2]. For present purposes, the γ detection is crucial. A barrel of 1380 CsI crystals, each of 16 radiation lengths, covers 98% of the solid angle around a liquid hydrogen target 4 cm long. Immediately surrounding the target are two multiwire chambers which are used here to veto events producing charged particles. The resulting trigger selects final states containing only neutral particles. The trigger includes a coincidence with silicon counters which detect the incident $\bar{p}$ just upstream of the target; it also includes a downstream veto which eliminates non-interacting beam particles and elastic scattering in the diffraction region.

Events are processed in a way following closely the measurement of $3\pi^0$ final states [3]. The analysis chain selects 8γ final states and then pairs up photons to make $\eta\pi^0\pi^0\pi^0$ combinations. The final selection of events demands a confidence level $> 10\%$ for this final state and confidence levels $< 1\%$ for $4\pi^0$ or $\omega\omega\pi^0$, the main contaminating channels. This procedure yields 6993 events at 1.94 GeV/c from an initial sample of 1469K all-neutral triggers. From a Monte Carlo simulation of the detector and analysis chain, the efficiency for selecting $\eta\pi^0\pi^0\pi^0$ events is 9.7%. In the data sample, there is a conspicuous signal due to $\bar{p}p \rightarrow \eta\eta \rightarrow \eta(\pi^0\pi^0\pi^0)$, and a small one due to $\bar{p}p \rightarrow \pi^0\eta' \rightarrow \pi^0(\eta\pi^0\pi^0)$, which are not of interest for the present study. When they are rejected by kinematic fits, 4627 events are left at 1.94 GeV/c (and 3406 at 1.2 GeV/c).

From a study of $4\pi^0$ and $\omega\omega\pi^0$ channels, the contamination in the $\eta\pi^0\pi^0\pi^0$ sample is estimated to be $< 5\%$. Any background which survives is expected to be close to a phase-space distribution for $\eta\pi\pi\pi$, because of the large number of kinematic combinations.

The data are fitted by the maximum likelihood method to the following channels, which include a 2^+ resonance $f_2(2135)$ and two 2^- resonances which we call $\eta_2(1645)$ and $\eta_2(1875)$:

$$
\begin{aligned}
\bar{p}p &\rightarrow f_2(1270)a_0(980) \rightarrow (\pi\pi)(\eta\pi) && (1)\\
&\rightarrow a_2(1320)\sigma \rightarrow (\eta\pi)(\pi\pi) && (2)\\
&\rightarrow a_0(980)\sigma \rightarrow (\eta\pi)(\pi\pi) && (3)\\
&\rightarrow f_1(1285)\pi \rightarrow (a_0[980]\pi)\pi && (4)\\
&\rightarrow \eta_2(1645)\pi \rightarrow (a_2[1320]\pi)\pi && (5)\\
&\rightarrow \eta_2(1645)\pi \rightarrow (f_2[1270]\eta)\pi && (6)\\
&\rightarrow \eta_2(1875)\pi \rightarrow (f_2[1270]\eta)\pi && (7)
\end{aligned}
$$

$$\rightarrow \quad f_2(2135)\pi \rightarrow (a_2[1320]\pi)\pi \tag{8}$$

$$\rightarrow \quad f_2(2135)\pi \rightarrow (f_2[1270]\eta)\pi \tag{9}$$

$$\rightarrow \quad \pi_2(1670)\eta \rightarrow (f_2[1270]\pi)\eta. \tag{10}$$

In addition, an incoherent phase-space background is required to provide a broad backdrop to the narrow states in channels (1) to (10). In channels 2 and 3, σ stands for the $\pi\pi$ S-wave amplitude which rises slowly through 90° over a wide mass range, 600 to 950 MeV; it is given accurately up to 1.3 GeV by the prescription of Zou and Bugg [4].

Fig. 1(a) displays the scatter plot at 1.94 GeV/c for combinations $\pi_i\pi_j$ against the other pair of particles $\eta\pi_k$; all six permutations of π^0 are plotted, and included coherently in the amplitude analysis. Channel 2, $a_2\sigma$, appears as a vertical $a_2(1320)$ band; channel 1, f_2a_0, is visible at the intersection of $f_2(1270)$ and $a_0(980)$ bands. A significant point is that the $f_2(1270)$ signal is biased towards 1200 MeV; the amplitude analysis associates this with an $\eta\pi\pi$ resonance decaying through $f_2(1270)$ close to threshold, channels 6 or 7.

Figs. 1(b) and (c) show mass projections of $\eta\pi\pi$ combinations and $3\pi^0$. Fig. 1(b) is plotted before removal of the η' by kinematic fitting, in order to illustrate the strength of that signal. From 1500 to 1900 MeV there is a broad bump due to (i) $\eta_2(1645)$ and (ii) strong production of $f_2(1270)\eta$ close to threshold. Fig. 1(c) shows a peaking at high 3π mass, partially due to $\pi_2(1670)$, but partly due to a reflection of $f_2(1270)a_0(980)$.

We now outline the amplitude analysis [5], taking channel 5 as an example. The initial $\bar{p}p$ system has helicity ±1 or 0. In the process $\bar{p}p \to X\pi^0$, the resonance X is produced with a component of spin along the beam direction $\lambda = \pm2$, ±1 or 0 for the channels we fit. Only the decay of X is described in detail by the fitted amplitudes. The production process is parametrised crudely by factors $\exp(\alpha\tau^2)$, where $\tau = 2p_1p_2\cos\theta$ and $p_{1,2}$ are centre of mass momenta of $\bar{p}$ and X, and θ is the centre of mass angle of X; apart from this exponential factor, which gives a small peaking of events forwards and backwards, we integrate over the production and make no attempt to isolate the $\bar{p}p$ partial waves which contribute. (There are too many spin states for a unique analysis of the initial state). The $\lambda = \pm2$ amplitudes also include a factor $\sin\theta$ due to transfer of orbital angular momentum from initial to final state.

The decay of X is described in full in terms of angles (γ, ϵ) for decay of X to $a_2(1320)\pi$ (in this example) and angles (α, β) for decay of $a_2(1320)$ to $\eta\pi$. It may be shown that cross sections contain no interferences between states of X with different λ. For a given λ, interferences between all channels are examined and those which are significant are kept. Since there are many possible initial $\bar{p}p$ states, the interference is constrained to lie within the range 0 (no coherence) to ±1 (full coherence) times the maximum possible interference term. These interferences are important. Channels 1 and 2 act as interferometers giving phase information on the remaining channels. This provides accurate information on the mass of $\eta_2(1645)$.

The two resonances $\eta_2(1645)$ and $f_2(2135)$ are clearly visible by eye when appropriate plots are made, as is the threshold production of $f_2(1270)\eta$. In order to investigate $X \to \eta\pi_i\pi_j$, events are first grouped in Fig. 2 into four intervals of invariant mass $M(\eta\pi_i\pi_j)$. The vertical axis shows $M(\pi_i\pi_j)$; both $M(\eta\pi_i)$ and $M(\eta\pi_j)$ combinations are plotted horizontally. In all, six combinations of the three pions are considered.

Firstly, we describe the evidence for $f_2(2135)$. Fig. 2(a) shows the scatter plot for the $\eta\pi\pi$ mass range 1950 to 2250 MeV. At the intersections of the horizontal $f_2(1270)$ and vertical $a_2(1320)$ bands, there is a strong cross due to interference. It is not due to $\bar{p}p \to f_2(1270)a_2(1320)$, which has a threshold well above the total available centre of mass energy, 2409 MeV. Instead the cross on Fig. 2(a) is due to a single resonance which decays to both $a_2(1320)\pi$ and $f_2(1270)\eta$. These are treated as fully coherent in the fit. Interference between channels 1 and 2 does not contribute significantly.

One expects $q\bar{q}$ $^3F_4$, $^3F_3$ and $^3F_2$ resonances in the mass range around 2050 MeV; some of these are already established. One might anticipate that the 3^{++} $I = 0$ resonance would decay naturally to $\eta\pi\pi$. It therefore comes as a surprise that the data firmly demand $J^{PC} = 2^{++}$ for the signal at 2135 MeV if it is treated as a single resonance. This gives a highly significant improvement to log likelihood of $\Delta S = 50.2$. (For comparison, the $f_1(1285)$ signal clearly visible in Fig. 1(b) gives $\Delta S = 45.3$). Other J^P have been tried and give much smaller values of ΔS shown in Table 1.

From our data alone, $M = 2135 \pm 20 \pm 45$ MeV, $\Gamma = 250 \pm 25 \pm 45$ MeV for this resonance; the first error is statistical and the second covers systematic variations observed in all fits with differing ingredients. The GAMS group [6] has observed a 2^{++} resonance in $\eta\eta$ with a mass of 2175 ± 20 MeV and width 150 ± 35 MeV. If these values are substituted in the fit, S deteriorates by only 5, so it is possible that the resonance in our data can be identified with $f_2(2175)$. Whatever its identity, it turns out that conclusions about $\eta_2(1645)$ and the $f_2(1270)\eta$ threshold region are almost completely decoupled from it. We remark that the Particle Data Group [7] brackets the GAMS resonance with one at 2104 MeV observed by the E760 experiment [8]. However, there was no J^P determination in the latter experiment and there is new evidence [9] that the 2104 MeV resonance may have different quantum numbers; hence we compare only with the GAMS result.

The threshold $f_2(1270)\eta$ effect appears in Fig. 2(b) as a horizontal band near an $\eta\pi\pi$ mass of 1850 MeV. It will be discussed below. The resonance $\eta_2(1645)$ is revealed in Fig. 2(c) as a vertical $a_2(1320)$ band. In order to display both effects quantitatively, further cuts are applied in Fig. 3.

In Fig. 3(a), $\eta_2(1645)$ is displayed by requiring $\eta\pi\pi$ combinations which contain $a_2(1320)$ but not $f_2(1270)$. For a final state $\eta\pi_i\pi_j$, events are selected if either mass $M(\eta\pi_i)$ or $M(\eta\pi_j)$ lies within ± 55 MeV of $a_2(1320)$, i.e. within $\pm$ one half-width. They are rejected if $M(\pi_i\pi_j)$ lies between 925 and 1455 MeV. All six combinations of i and j are included. The dashed curve shows phase space, corrected for detector acceptance and normalised to the whole data set; its absolute normalisation exhibits the effect of the kinematic cuts. The data require a significant $\eta_2(1645) \rightarrow a_2(1320)\pi$ signal above phase space. It improves log likelihood by a highly significant amount, ~ 67. The full histogram on Fig. 3(a) shows the maximum likelihood fit (with statistics limited by the Monte Carlo simulation of the detector).

In Fig. 3(b), the converse selection is made enhancing $f_2(1270)\eta$ and rejecting $a_2(1320)\pi$. A cut is applied selecting $\pi_i\pi_j$ masses from 1100 to 1370 MeV. This interval is deliberately asymmetric about $f_2(1270)$ so as to include threshold production, which biases the f_2 mass to low values. In order to eliminate $\eta_2(1645)$, events are rejected if either $M(\eta\pi_i)$ or $M(\eta\pi_j)$ lies within ± 120 MeV of $a_2(1320)$. There is a strong signal in the data from 1750 to 1925 MeV. Most of the signal is due to channel (7), $f_2(1270)\eta$. A part, about 35%, is due to constructive interference between this channel and channels (1) and (10), i.e. $f_2(1270)a_0(980)$ and $\pi_2(1670)\eta$; if these channels are removed from the fit, the shape of the peak around 1850 MeV is unaffected.

This threshold signal has two possible explanations. One possibility is a second 2^{-+} resonance with $M = 1875 \pm 20 \pm 35$ MeV, $\Gamma = 200 \pm 25 \pm 45$ MeV. This resonance improves S by 54. The full histogram shows the corresponding maximum likelihood fit. The resonance is so close to threshold that it is most likely to be produced with $L = 0$ between $f_2(1270)$ and η in the final state, i.e $J^{PC} = 2^{-+}$. However, we have tried $L = 1$ alternatives, which give poorer fits: $\Delta S = 24$ for 3^{++}, 21 for 2^{++} and 12 for 1^{++}.

A second interpretation is that the signal in Fig. 3(b) comes from the high mass tail of $\eta_2(1645)$ feeding the opening channel $f_2(1270)\eta$. To examine this, we have used a two-channel Flatté formula to fit $\eta_2(1645)$. Let $a_2\pi$ and $f_2\eta$ be channels A and B. Amplitudes are written:

$$f_i^\lambda = \frac{\Lambda_i^\lambda BW(i)\ \exp(i\phi)}{s - M^2 + iM(\Gamma_A + \Gamma_B)}, \qquad i = A, B, \tag{11}$$

where Λ_i are real. The expression $BW(i)$ stands for a Breit-Wigner amplitude describing decays of either $f_2(1270)$ or $a_2(1320)$. The spin index λ runs $\lambda = 0, 1, 2$. The phase ϕ_i of the amplitude is different for $f_2\eta$ or $a_2\pi$ final states whether there is one resonance or two; it arises from rescattering in initial or final or intermediate states and can be quite different for the two channels. It is however independent of spin λ. The width Γ_A due to $a_2(1320)\pi$ is taken as constant. Allowance is made for $f_2(1270)\eta$ using a Fermi function:

$$\Gamma_B = \frac{\Gamma_A/(5.24r(\eta\pi^0\pi^0))}{1 + \exp([M_t^2 - s]/b)}. \tag{12}$$

The denominator approximates the ratio of $f_2\eta$ phase space to $a_2\pi$ with $b = 0.346$ GeV^2 and M_t the threshold mass, 1822 MeV. The factor $r(\eta\pi^0\pi^0) = a_2\pi/f_2\eta$ weights Γ_B by the fitted intensity $\sum_\lambda \Lambda_B^2$ of the $f_2\eta$ channel, summed over $\lambda = 0 - 2$, and divides by the corresponding intensity for $a_2\pi$. The factor 5.24 allows for (i) the branching ratio 0.162 of $a_2(1320)$ to $\eta\pi$, (b) the branching fraction 0.849/3 of $f_2(1270)$ to $\pi^0\pi^0$, and (c) three charge states for $a_2(1320)\pi$. In practice, the term Γ_B in the denominator is small compared with Γ_A and has only a marginal effect, cutting off $\eta_2(1645)$ slightly at high masses.

Fig. 4 shows S = log likelihood v. fitted mass for a single resonance described by the Flatté form. In Fig. 4(a), data are at a beam momentum of 1.94 GeV/c. There is a well determined minimum due to $\eta_2(1645)$, giving $M = 1645 \pm 14 \pm 15$ MeV. There is strong interference with channel 2, $a_2(1320)\sigma$, which helps fix the phase and hence an accurate mass determination for $\eta_2(1645)$.

There is not much phase space for $\eta_2(1645) \to a_2(1320)\pi$, so an S-wave final state is the most likely, i.e. $J^{PC} = 2^{-+}$. We have tried alternative fits with $L = 1$ and $J^{PC} = 1^{++}$, 2^{++} or 3^{++}; a Blatt-Weisskopf centrifugal barrier is included with radius 0.6 fm. These give much poorer fits and no significant optima for any physical mass of X. Since there are $q\bar{q}$ 1^{++} and 2^{++} radial excitations expected in this mass range, we have also tried adding these to $\eta_2(1645)$ in the fit, but get no significant improvement. D-wave decays $\eta_2(1645) \to a_2(1320)\pi$ are also found to be negligible.

The fit with two separate resonances $\eta_2(1645)$ and $\eta_2(1875)$ is better by $\Delta S = 15$ than with the Flatté form. This difference is marginal. Projections on to $M(\eta\pi\pi)$ from the two fits are very similar and do not distinguish cleanly between them. Data at a $\bar{p}$ momentum of 1.2 GeV/c are similar to those at 1.94 GeV/c and again $\eta_2(1645)$ and the $f_2(1270)\eta$ threshold enhancement are clearly visible in the raw data. They differ in two respects. An obvious difference is that the available mass range is reduced and $f_2(2135)$ is absent. Secondly, $\eta_2(1645)$ is produced rather more weakly compared with $\eta_2(1875)$. Log likelihood is now worse for the Flatté fit by 23.2 than for the fit with two separate resonances. This is still not completely decisive. However, there is one interesting feature. Fig. 4(b) shows log likelihood for these data v. the resonance mass in the Flatté formula. There is now a double minimum, the stronger one near 1875 MeV. This suggests the presence of two resonances. The dashed curve of Fig. 4(b) shows the fit obtained omitting the phase-space contribution. Although the fit is poorer well away from narrow resonances, the mass of the 1875 MeV resonance, if it exists, is now determined more precisely.

Table 2 shows the effects of dropping individual channels and refitting remaining components. Table 3 shows the effects of interference terms; only those giving $\Delta S > 10$ in one of the fits is kept.

We now discuss the interpretation of the results. The $\eta_2(1645) \to a_2\pi$ signal may be interpreted naturally as a $q\bar{q}\ ^1D_2$ state, which is expected near this mass as partner to $\pi_2(1670)$; the latter has a similar decay mode to $f_2(1270)\pi$. There is a physics argument in favour of two separate resonances $\eta_2(1645)$ and $\eta_2(1875)$ from the observed strengths of $f_2\eta$ and $a_2\pi$ signals. A $q\bar{q}$ state is expected to couple equally to $f_2\eta$ and $a_2^0\pi^0$, except for a factor 0.64 which allows for the $s\bar{s}$ content of the η. Following similar arithmetic to eqn. (12), the expected ratio of strengths for $\eta_2(1645) \rightarrow a_2\pi$ and $f_2\eta$ is

$$r(\eta\pi^0\pi^0) = \sum_\lambda |\Lambda^\lambda_{1320}|^2/|\Lambda^\lambda_{1270}|^2 = \frac{0.162 \times 3}{0.849 \times 0.64} = 0.89. \qquad (13)$$

The observed ratio is a factor 10 to 20 smaller than this. In Fig. 3(a) there are $\sim$ 30 events per bin fitted to $\eta_2(1645)$ at its peak. Yet integrated phase space favours $a_2\pi$ by a factor of ~ 3 over $f_2\pi$. Furthermore, a Breit-Wigner form for $\eta_2(1645)$ attenutates it at the peak of Fig. 3(b) by a factor 4 to 8, depending on its width. The observed $f_2(1270)\eta$ signal is $\sim$ 35 events per bin, similar to the $\eta_2(1645)$ signal *at its peak.* The only way to fit both channels with a Flatté formula is to require the $f_2\eta$ coupling to be very much larger than expected for a $(u\bar{u} + d\bar{d})/\sqrt{2}$ state at 1645 MeV, for example due to a large $s\bar{s}$ component. In view of the close agreement in mass between $\eta_2(1645)$ and $\pi_2(1670)$, this does not seem plausible.

For $f_2(2135)$, the ratio of decay rates observed in $\eta\pi^0\pi^0$ final states is $r(\eta\pi^0\pi^0) = a_2(1320)\pi/f_2(1270)\eta = 1.41 \pm 0.18$. This value is rather higher than eqn. (13), perhaps due to the $L = 1$ centrifugal barrier, which will favour $a_2\pi$.

We now compare with data from other experiments. Mark III data [10] on $J/\psi \rightarrow \gamma(\eta\pi\pi)$ show a definite mass peak at $\sim$ 1875 MeV, having a width compatible on its upper side with our value of 200 MeV. No J^P analysis has been reported of this peak. It is important to study $\bar{K}K^*$ channels for further clues. A ninth member of the nonet is expected around 1875 MeV, but dominant KK^* decay modes are anticipated for an $s\bar{s}$ state. So it is not obvious that $\eta_2(1875)$ should be interpreted as the ninth member of the nonet.

Crystal Ball data on $\gamma\gamma \rightarrow \eta\pi^0\pi^0$ [11] show a 2^{-+} signal with mass $1881 \pm 32 \pm 40$ Mev and width $221 \pm 92 \pm 44$ MeV. The CELLO collaboration has also reported evidence for an $I = 0$ $J^{PC} = 2^{-+}$ resonance in $\eta\pi\pi$ at about 1850 MeV [12]. It seems unlikely to be the high mass tail of $\eta_2(1645)$ since any signal around 1645 MeV is weaker. There is evidence in the Crystal Ball data for decays 53% to $a_2(1320)\pi$ and 47% to $a_0(980)\pi$, while we see no signal in the latter channel. However we warn that $\eta_2(1875) \rightarrow f_2(1270)\eta$ produces a mass distribution which kinematically mimics $a_0(980)\pi$. The $f_2(1270)$ is almost at rest in the $\eta_2(1875)$ decay frame and decay pions form an $\eta\pi$ mass combination centred just above $a_0(980)$, but with an angular distribution different from $\eta_2(1875) \rightarrow a_0\sigma$ with L=2.

Anderson et al. [13] have pointed out that the Crystal Ball signal is a factor 40 – 400 larger than expected for a $q\bar{q}$ $^1D_2$ state. A hybrid, $q\bar{q}g$, is another possibility [14]. In view of the signal in Mark III data, a glueball is also a candidate, but one must then explain the $\gamma\gamma$ coupling. Because $\eta_2(1875)$ lies very close to threshold, its wave function must contain a long-range $f_2\eta$ component (like the NN component of the deuteron, which has small binding energy). We speculate that $\gamma\gamma$ coupling to this component might explain the Crystal Ball and Cello observations.

We have searched for evidence of $\eta_2(1875) \rightarrow a_2\pi$ independent of $\eta_2(1645) \rightarrow$

$a_2\pi$ but have found none at this beam momentum. The data do not separate two neighbouring resonances well. For $\eta_2(1875)$, they give an optimum for the ratio of events in $\eta\pi^0\pi^0$ final states $r(\eta\pi^0\pi^0) = a_2(1320)\pi/f_2(1270)\eta = 0$, but with a sizeable error 0.8. We have also searched for further decay modes of $\eta_2(1645)$, $\eta_2(1875)$ and $f_2(2135)$ to $a_0(980)\pi$, $\sigma\eta$ or a separate $f_0(980)\eta$. The last of these is treated individually because of the possibility that it couples to $\bar{p}p$ or resonances with different strength from the remaining $\pi\pi$ S-wave. However, we find no significant signals with orbital angular momentum $L = 2$ in the final state.

In conclusion, we regard the evidence for $\eta_2(1645) \to a_2(1320)\pi$ as definitive. There is a strong $f_2(1270)\eta$ signal close to threshold, which can be fitted experimentally to the high mass tail of $\eta_2(1645)$, but it is so strong that a second $\eta_2(1875)$ seems more likely. Data on other channels, e.g. $a_2(1320)^{\pm}\pi^{\mp}$, are needed to help resolve this issue.

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Figure Captions

Fig. 1. (a) The scatter plot for $M(\pi_i\pi_j)$ v. $M(\eta\pi_k)$ at 1.94 Gev/c, 6 combinations. (b) Projection of $M(\eta\pi\pi)$, 6 combinations, before removing $\eta'(958)$ by kinematic fitting. (c) Projection of $M(3\pi^0)$. The shaded areas show Monte Carlo simulations of phase space, modified by detector acceptance. Masses are in MeV.

Fig. 2. Scatter plots for $M(\pi_i\pi_j)$ v. $M(\eta\pi_i)$ or $M(\eta\pi_j)$, 6 combinations, for four bands of $M(\eta\pi_i\pi_j)$: (a) 1.95 – 2.25 GeV, (b) 1.75 – 1.95 GeV, (c) 1.55 – 1.75 GeV, (d) 1.35 – 1.55 GeV. One unphysical bin has been filled with a constant number, so that individual plots are directly comparable on an absolute scale. In (c), $\eta_2(1645) \to a_2(1320)\pi$ is visible as a vertical band. In (b), $\eta_2(1875) \to f_2(1270)\pi$ gives a horizontal band. The interference cross in (a) between $f_2(1270)$ and $a_2(1320)$ is evidence for $f_2(2135)$.

Fig. 3. Projections of 6 combinations of $M(\eta\pi_i\pi_j)$, (a) selecting $a_2(1320)$ and excluding $f_2(1270)$ and $f_0(980)$: $M(\pi_i\pi_j)$ outside the range 0.925 to 1.455 GeV, and either $M(\eta\pi_i)$ or $M(\eta\pi_j) = 1.3182 \pm 0.055$ GeV, (b) for $M(\pi_i\pi_j)$ within an $f_2(1270)$ window between 1.1 and 1.37 GeV, and excluding events in a window around $a_2(1320)$ from 1.2 to 1.436 GeV, (c) as (b) for the fit with the Flatté formula. Full curves show the maximum likelihood fit with the statistics of the Monte Carlo simulation. The dashed curves show phase space normalised to the whole data set.

Fig. 4. S = log likelihood v. $M(\eta\pi\pi)$ for fits with the Flatté form, (a)

at 1.94 GeV/c, (b) at 1.2 GeV/c. In (b), the full line is obtained including the phase-space contribution in the fit, and the dashed line without it. All curves are normalised to zero at the minimum.

L	J^P	ΔS
0	2^{-+}	13.0
	1^{++}	6.1
1	2^{++}	50.2
	3^{++}	10.0
	0^{-+}	10.3
	1^{-+}	1.6
2	2^{-+}	1.1
	3^{-+}	8.0
	4^{-+}	3.4
3	4^{++}	0.2

Table 1: Improvements ΔS to the fit for various J^P of the 2135 MeV resonance; L is the orbital angular momentum between $a_2(1320)$ and π or between $f_2(1270)$ and η.

Channel	(a)	(b)
1	-29.4	-23.4
2	-16.5	-13.1
3	-12.8	-7.6
4	-45.3	-49.7
5	-67.4	-
6	-	-49.8
7	-53.8	-
8+9	-50.2	-54.0
10	-76.4	-57.1

Table 2: Changes ΔS in log likelihood when each component is dropped from the fit to data at 1.94 GeV/c (a) with separate $\eta_2(1645)$ and $\eta_2(1875)$ resonances, (b) with the Flatté formula.

Fit	Channels	ΔS
	2 $\times$ 5	-31.0
	5 $\times$ 7	-20.6
(a)	1 $\times$ 10	-23.9
	5 $\times$ 10	-10.6
	7 $\times$ 10	-11.7
	1 $\times$ 5+6	-5.5
(b)	2 $\times$ 5+6	-12.1
	1 $\times$ 10	-8.0
	5+6 $\times$ 10	-13.2

Table 3: Changes ΔS in log likelihood due to interferences in fits (a) with separate $\eta_2(1645)$ and $\eta_2(1875)$ resonances, (b) with the Flatté formula.