High statistics study of $f_0(1500)$ decay into $\eta\eta$

Crystal Barrel Collaboration

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A partial wave analysis of the reaction $\bar{p}p \to \pi^0\eta\eta$ has been performed, using a high quality, high statistics data set of 198,000 events. In addition to the $f_0(1370)$, a second scalar resonance decaying into $\eta\eta$, the $f_0(1500)$, with mass $m = (1505 \pm 15)$ MeV and width $\Gamma = (120 \pm 30)$ MeV has to be introduced to describe the data.

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In a recent letter [1] we have reported the existence of three scalar isoscalar $\pi\pi$ resonances in the 1000–1500 MeV mass range. The $\pi\pi$ interactions were studied in the reaction $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0\pi^0$ by stopping antiprotons in liquid hydrogen (LH_2). Apart from the well known $f_0(980)$, two other resonances were found with masses of (1330 ± 50) MeV and (1500 ± 15) MeV, which we call $f_0(1370)$ and $f_0(1500)$, respectively. The width of the $f_0(1500)$ was determined to (120 ± 25) MeV; the width of the $f_0(1370)$ was found to depend on the number of $\pi\pi$ S–wave poles assumed in the analysis. With three S–wave poles the $f_0(1370)$ pole had a width of 760 MeV, whereas with four poles a narrower width of 300 MeV was found.

In this letter we present a new analysis of the reaction:

$$\bar{\mathrm{p}}\mathrm{p} \to \pi^0\eta\eta \qquad (1)$$

based on high statistics, high quality data obtained with the Crystal Barrel detector operating at the Low Energy Antiproton Ring at CERN.

A first analysis of reaction (1), based on limited statistics (one tenth of the present data) [2], provided the first indications on the presence of two $\eta\eta$ scalar resonances in the mass range 1350 – 1600 MeV. The more detailed analysis presented now, based on high statistics data obtained with a dedicated trigger, confirms the previous observations. These new results supersede those of [2] (A χ^2 comparison of the high statistics Dalitz plot to the sample used in [2] shows an excellent agreement between the two sets of data).

Another analysis, based again on about one tenth of the presently available statistics, succeeded in giving an interpretation of the $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\eta\eta$ [2] and $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\pi^0\pi^0$ [3] data simultaneously [4]. This approach, which constrained the $\pi\pi$ and $\eta\eta$ S–waves to exhibit the same poles, found also that two scalar resonances had to be introduced in the 1350 – 1600 MeV mass range, both of them coupling to $\pi\pi$ and $\eta\eta$. In [4], the masses and widths of these resonances were found at $m = (1365^{+20}_{-55})$ MeV, with $\Gamma = (268\pm 70)$ MeV and $m = (1520 \pm 25)$ MeV with $\Gamma = (148 \pm 25)$ MeV.

In the present analysis, the $\eta\eta$ S–wave is determined independently of the $\pi\pi$ S–wave. It turns out, a posteriori, that the pole positions found for the $\eta\eta$ S–wave agree with those of the $\pi\pi$ S–wave as determined in the most recent analysis of $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\pi^0\pi^0$ [1].

We refer to [5] for a detailed description of the Crystal Barrel detector. Antiprotons with a momentum of 200 MeV/c stop in the center of the detector and annihilate with protons of the liquid hydrogen target. The main component of the detector for the present data set is an electromagnetic calorimeter with 1380 CsI crystal modules.

Data on reaction (1) were extracted from the 6γ final state which used the $\gamma\gamma$ decay mode of each of the pseudoscalar mesons. We accumulated 16.8 million events with a *zero–prong* trigger, i.e. requiring an antiproton entering and not leaving the target and no charged tracks in the wire chambers surrounding the target. In the first step of the analysis we rejected events with residual track elements and kept 15 million *all–neutral* events. From these events we chose those having exactly 6 electromagnetic showers. This left 3.2 million events. The data set was further reduced by a 4C kinematic fit imposing energy and momentum conservation to 1.4 million events. The remaining data sample was then subjected to a series of 7C kinematic fits ($\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta'$, $\pi^0\eta\eta'$, $\omega\omega$(8C) with $\omega \to \pi^0\gamma$). After this procedure we found 53,000 $\pi^0\eta\eta$ events with a probability larger than 1%. Because the channel $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\eta\eta$ is less strong than $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0\pi^0$ or $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0\eta$ for instance, the background contribution in the final state $\pi^0\eta\eta$ is not negligible. Therefore we required a confidence level of 10% for the kinematic fit to the $\pi^0\eta\eta$ hypothesis and applied a cut (1%) to the competing kinematic hypotheses. Finally we kept a data sample of 31,000 $\pi^0\eta\eta$ events. The residual background contamination, mainly from feedthrough of the 7γ final state $\pi^0\pi^0\omega$, is estimated by a full detector Monte Carlo simulation based on the CERN program package GEANT [6]. The background is distributed randomly over the Dalitz plot, and represents approximately 4.5% of the signal.

The detection efficiency including the acceptance variation over the Dalitz plot was deter-

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mined to be (25.7 ± 2.7)%. The error includes the acceptance variation. For a calculation of the branching ratio the number of $\pi^0\eta\eta$ events was normalized to the number of $\omega\omega$ events observed in the present data set. The branching ratio of the reaction $\bar{\mathrm{p}}\mathrm{p} \to \omega\omega$ was taken from [7]. Thus we get

$$\mathrm{BR}(\bar{\mathrm{p}}\mathrm{p} \to \pi^0\eta\eta) = (2.0 \pm 0.4) \cdot 10^{-3} \tag{2}$$

which is in good agreement with the value reported in [2].

In order to improve the statistics for the $\pi^0\eta\eta$ channel we have set up a trigger enhancing the fraction of events on tape for this channel. A hardware trigger required the absence of tracks from charged particles in the drift chamber and detection of 5 to 7 photons in the calorimeter. A fast on–line reconstruction program then selected events having exactly six photons and calculated the two–photon invariant masses (with 15 combinations per event). Events were accepted when the six photons could be combined to form one π^0 and two η mesons. The triggered data underwent the same analysis chain as described above; 167,000 events were found. A comparison of the two Dalitz plots, the special triggered with the zero–prong triggered data set, gives a $\chi^2 = 1.08$ per bin showing that both samples are compatible. Therefore we use the combined data set for the partial wave analysis (198,000 events).

In fig. 1 the Dalitz plot of the reaction $\bar{\mathrm{p}}\mathrm{p} \to \pi^0\eta\eta$ is shown. Because of the indistinguishability of the two η mesons, each event enters the Dalitz plot twice. Fig. 2 and fig. 3 give the $\pi^0\eta$ and $\eta\eta$ projections, respectively.

First of all we notice the strong enhancement in the middle of the Dalitz plot produced by a constructive interference of the two bands from the $a_0(980)$, here observed in its $\pi^0\eta$ decay mode. A further contribution to this enhancement is due to a band which crosses the Dalitz plot at an $\eta\eta$ invariant mass around 1500 MeV (see fig. 3). An additional maximum is observed at a lower $\eta\eta$ invariant mass as a band in the top right region of the Dalitz plot.

The analysis presented here assumes that the Fermi–Watson theorem on two–body final state interactions applies to reaction (1) and that the Dalitz plot (fig. 1), which contains all the infor-

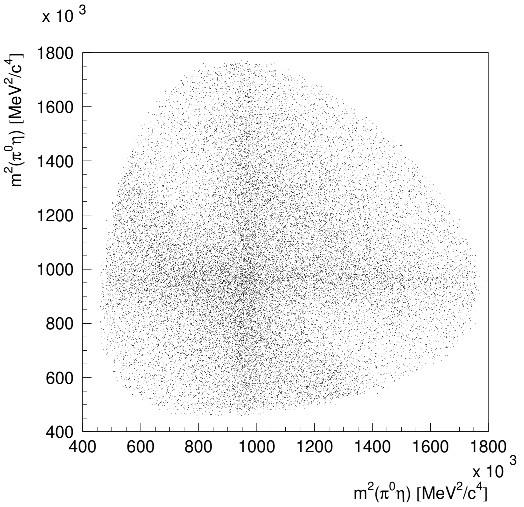

Fig. 1. *The $\pi^0\eta\eta$ Dalitz plot of the combined data set.*

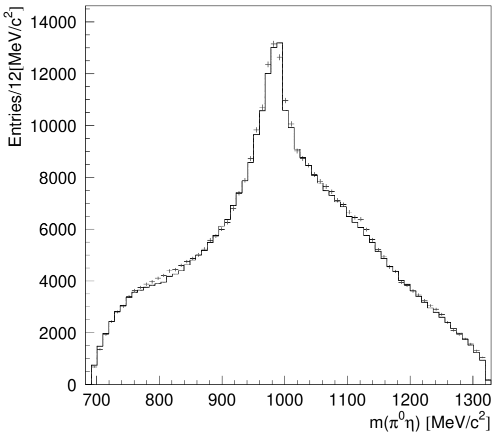

Fig. 2. *The projection of the $\pi^0\eta$ system with fit superimposed (crosses: data, histogram: fit described in the text).*

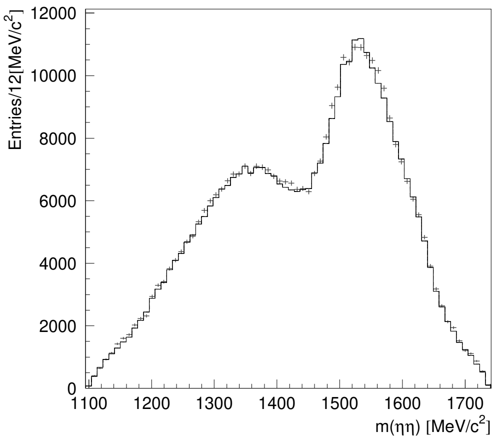

Fig. 3. *The projection of the $\eta\eta$ system with fit superimposed (crosses: data, histogram: fit described in the text).*

mation on three–body annihilations at rest, can be analyzed in terms of a superposition of amplitudes of the form:

$$\mathcal{A}_{J^{PC}} = \sum Z_{J^{PC},L,\ell}(\boldsymbol{p},\boldsymbol{q})F^{\ell}(\boldsymbol{q})B^{L}(\boldsymbol{p}) \tag{3}$$

The initial $\bar{\mathrm{p}}\mathrm{p}$ state is determined by its quantum numbers J^{PC}. The final state is characterized by the quantum numbers L and ℓ, where L is the angular momentum between the dimeson and the recoil meson of momenta $\pm\boldsymbol{p}$, ℓ is the angular momentum of the mesons into which the dimeson splits. Their momenta in the dimeson rest frame is $\pm\boldsymbol{q}$. The final state has $C=+1$ which restricts the allowed initial states to ${}^1\mathrm{S}_0(J^{PC}{=}0^{-+})$, ${}^3\mathrm{P}_1(J^{PC}{=}1^{++})$ and ${}^3\mathrm{P}_2(J^{PC}{=}2^{++})$.

The angular distributions are calculated following the method of Zemach [8] and are included in the amplitude by the spin–parity function $Z_{J^{PC},L,\ell}$. The angular momentum barrier factors $B^L(p)$ for the meson with respect to the dimeson are taken from [9].

In this analysis the dynamical amplitude F^{ℓ} is described within the K–matrix formalism [9] in an extension to production processes [10]. We suppress the index ℓ and obtain

$$F = (\mathbb{1} - iK\rho)^{-1}P \tag{4}$$

where $\mathbb{1}$ is the identity matrix and ρ is the two–body phase space factor. Note that ρ is imaginary below the associated threshold (e.g. $\mathrm{K}\bar{\mathrm{K}}$ for $\pi^0\eta$). The production vector P is given by a sum over resonance poles (with summation index α) produced with complex strengths β_α; the resonances couple to the different final states i with couplings $g_{\alpha i}$:

$$P_i = \sum_{\alpha} \frac{\beta_\alpha g_{\alpha i} B_i^{\ell}}{m_\alpha^2 - m^2}, \tag{5}$$

where B_i^{ℓ} is the angular momentum barrier factor for the resonance of spin ℓ decaying into two pseudo–scalars [9]. The coupling to different channels is achieved by an appropriate choice of a K–matrix

$$K_{ij} = \sum_{\alpha} \frac{g_{\alpha i} g_{\alpha j} B_i^{\ell} B_j^{\ell}}{m_\alpha^2 - m^2} \tag{6}$$

In the most simple case of one resonance which couples to one channel this formalism reduces to the Breit–Wigner formula.

We now outline our analysis strategy: In the analysis of the $\pi^0\pi^0\eta$ final state [11], which is dominated by the $\pi\pi$ and $\pi\eta$ S–wave final states, we inferred the S–wave $\pi\pi$ scattering amplitude from the CERN–Munich phase shift analysis [12] and from K_{e4} decays [13] and used the information on $\bar{\mathrm{p}}\mathrm{p}{\to}\pi^0\pi^0\eta$ to investigate the properties of the $\pi\eta$ S–wave final state interactions. The first attempts to analyze the $\bar{\mathrm{p}}\mathrm{p}{\to}\pi^0\eta\eta$ reaction have shown that these data alone do not allow a simultaneous and unique determination of the $\pi^0\eta$ and $\eta\eta$ final states. We are therefore led, in a first step, to fix the pole positions of the $\pi\eta$ S–wave resonances to the values found in [11], i. e., to introduce two $2{\times}2$ K–matrix poles corresponding to the $a_0(980)$ and $a_0(1450)$ as obtained in [11] (leaving free, however, the production strength β_α).

For the $\eta\eta$ S–wave we use the 1×1 K–matrix formalism, introducing two to three poles, to parametrize this channel.

Both the $\pi\eta$ and $\eta\eta$ S–waves are assumed to be produced from the ${}^1\mathrm{S}_0$ $\bar{\mathrm{p}}\mathrm{p}$ initial state alone ($\ell = L = 0$). On the contrary, we leave open the possibility that tensor mesons (in the $\pi\eta$ and $\eta\eta$ final state) could be produced from S and P initial states ($^1S_0$, $^3P_1$, $^3P_2$): in this case, the contributions of the various initial states are added incoherently.

The only known 2^{++} $\pi\eta$ resonance which could be produced within the phase space available is the $a_2(1320)$: we therefore introduce this possibility in the fit, imposing its mass and width taken from [14].

The 2^{++} $\eta\eta$ system is not known as well as the 2^{++} $\pi\eta$ (and the available phase space extends up to $\approx$ 1700 MeV): we therefore leave free, in the fit, the possible presence of a 2^{++} $\eta\eta$ resonance with unknown mass and width produced from $^1S_0$ and/or $^3P_1$ and/or $^3P_2$.

Before fitting the amplitudes to the data, we subtract from the Dalitz plot a flat incoherent background corresponding to 4.5% of the total sample.

The fits described below are based on a χ^2 comparison of the experimental data and the squared amplitude (3), the Dalitz plot being divided into cells of 18523 MeV^2 $\times$ 18523 MeV^2. The minimum number of events per cell is 18.

The experimental distribution is corrected, for each cell of the Dalitz plot, by an acceptance factor (ranging between 1.0 and 1.22). This acceptance correction is obtained by generating phase–space distributed events which are then submitted to the same analysis chain as the real data.

An acceptable χ^2 is obtained with the introduction of three 1×1 K–matrix poles for the $\eta\eta$ S–wave: $\chi^2/\text{ndf} = 2332/(1798 - 27) = 1.32$. As can be seen on fig. 2 and 3, the quality of the fit is quite good. The fit yields the following K–matrix poles $K_i = (m_i + i\widetilde{\Gamma}_i/2)$ for the $\eta\eta$ S–wave:

K_1:	$m_1 = 1350$ MeV	$\widetilde{\Gamma}_1 = 217$ MeV
K_2:	$m_2 = 1569$ MeV	$\widetilde{\Gamma}_2 = 191$ MeV
K_3:	$m_3 = 130$ GeV	$\widetilde{\Gamma}_3 = 21$ MeV

The first two K–matrix $\eta\eta$ S–wave poles correspond to the T–matrix resonance parameters: $(m, \Gamma) = (1391, 298)$ MeV which we call $f_0(1370)$ and $(m, \Gamma) = (1501, 136)$ MeV which we call $f_0(1500)$.

The third K–matrix pole does not correspond to a resonance. It describes the continuous rise of the $\eta\eta$ phase beyond the phase space limit. It may also be considered as a simple parametrization of the "soft–pion" effect expected in these reactions, according to [15]. In any case its contribution is small (2.7%) whereas the $f_0(1370)$ and $f_0(1500)$ represent 12.5% and 26% of the $\pi^0\eta\eta$ channel, respectively. Repeating this fit without the third pole leads to a slightly worse χ^2 (χ^2/ndf=1.36) but does not modify the results obtained with 3 poles, in particular for the $f_0(1500)$. On the other hand, the 2–pole fit leads to a broadening of the $f_0(1370)$. Its width becomes approximately 600 MeV.

The contribution of $a_2(1320)$ is small but significant: 2.8% of $\bar{p}p \to \pi^0\eta\eta$ with $\Delta\chi^2$=343. Omitting this contribution does not modify the masses and widths of the $f_0(1370)$ and $f_0(1500)$ by more than $\Delta m = \pm 10$ MeV and $\Delta\Gamma = 15$ MeV.

The mass and width obtained for the 2^{++} $\eta\eta$ are $m = 1494$ MeV and $\Gamma = 155$ MeV with a contribution of 3%, 6.2% and 11.4% from $^1S_0$, $^3P_1$ and $^3P_2$, respectively. Omitting this tensor amplitude leads to a significantly worse fit (χ^2/ndf=1.74) but the conclusions on the $f_0(1370)$ and $f_0(1500)$ remain essentially unchanged. One cannot rule out that this 2^{++}–amplitude, parametrized here with one pole, is the result of two or even three interfering 2^{++} resonances. Indeed, one obtains an equally good fit if we introduce, in addition to the free pole, some $f_2(1270)$: the fit then yields 2% of $f_2(1270)$ and 20% of $X_2(1490)$ with $m = 1492$ MeV, $\Gamma = 118$ MeV. From the known $f_2(1270)$ production in $\bar{p}p \to \pi^0 f_2(1270)$, and $f_2(1270)$ partial widths [1], we expect a contribution of 1.4%. This 2^{++} $\eta\eta$ component in our fits may indeed hide an even more complex situation, with some contribution of not only $f_2(1270)$, but also of $f_2'(1525)$ and possibly an additional unidentified resonance. The essential point here is that, whatever the form of the 2^{++} $\eta\eta$ amplitude we use, the conclusions on the $f_0(1370)$ and $f_0(1500)$ remain unchanged.

Finally, we allow for a free adjustment of the $\pi\eta$ S–wave (with only one $2\times2-K$–matrix pole omitting $a_0(1450)$). The fit deteriorates (χ^2/ndf=1.44) and, what is even more significant, it yields unreasonable parameters for $a_0(980)$: $m = 995.4$ MeV, $\widetilde{\Gamma}_{\pi\eta} = 505.8$ MeV, $\widetilde{\Gamma}_{K\bar{K}} = 12$ MeV. However, even in these conditions the need for two $\eta\eta$ S–wave resonances is confirmed: ((m, Γ) = (1393, 232) MeV and $(m, \Gamma) = (1512, 130)$ MeV.

Several additional tests were performed to test the stability of the results. The $a_0(980)$ (which is observed very prominently in our data) was represented by a simple Breit–Wigner amplitude; this led to a mass of (981.8 ± 0.4) MeV and a width of (52.2 ± 0.9) MeV. Note that these errors reflect only the statistical precision of the data and not the systematic uncertainties due to the model dependence. The $\eta\eta$ interaction parameters also remain compatible with the values given above.

Since we have observed an $\eta\eta'$ threshold enhancement [16] near the mass of the $f_0(1500)$, we have also tried to fit the $\eta\eta$ S–wave, introducing a 2×2 K–matrix with $\eta\eta$ and $\eta\eta'$ as coupled channels; no significant changes in the resonance parameters were observed.

We also allowed the production of $\pi^0(\eta\eta)_{\mathrm{S-wave}}$ from the $^3\mathrm{P}_1$ state of the $\bar{\mathrm{p}}\mathrm{p}$ atom; this leads, however, to rather uncertain results, probably due to an over parameterization of the data.

The importance of $\bar{\mathrm{p}}\mathrm{p}$ P–state contribution to the annihilations when they come from antiprotons stopping in liquid hydrogen is not known. It is generally assumed to be small, in particular for $^3\mathrm{P}_1$ and $^3\mathrm{P}_2$ initial states, the only ones allowed here. Imposing pure $^1\mathrm{S}_0$ initial state, we got a nearly equally good fit, the $\pi^0\eta$ and $\eta\eta$ D–wave amplitudes coming out very small, the mass and width of the $f_0(1500)$ becoming 1505 MeV and 170 MeV, respectively, and the contribution of this resonance to the $\pi^0\eta\eta$ channel growing up to 31%.

Adding constant terms, alternatively to the production vector P or to the amplitude F does not lead to new solutions: indeed the constants were rejected by the fit.

We therefore conclude that two resonances are needed in the $\eta\eta$ S–wave. Taking into account the spread of the acceptable fits, we can quote the following masses and widths, with errors:

$$
\begin{aligned}
f_0(1370): \quad m &= (1360 \pm 35)\,\mathrm{MeV} && (7)\\
\Gamma &= (300 - 600)\,\mathrm{MeV} &&\\
f_0(1500): \quad m &= (1505 \pm 15)\,\mathrm{MeV} && (8)\\
\Gamma &= (120 \pm 30)\,\mathrm{MeV} &&
\end{aligned}
$$

The contribution of $f_0(1370)$ and $f_0(1500)$ to the $\pi^0\eta\eta$ channel is estimated to be between 10% and 25% and between 23% and 32%, respectively.

Evidence for two scalar $\eta\eta$ resonances was first reported by the GAMS collaboration [17] in a study of the charge exchange reaction $\pi^-\mathrm{p} \rightarrow \eta\eta\mathrm{n}$ with a 100 GeV/c pion beam. Two resonances were found with masses and widths of $(m, \Gamma) = (1220 \pm 40, 320 \pm 40)$ MeV and $(m, \Gamma) = (1575 \pm 45, 265 \pm 65)$ MeV. The latter resonance was also observed by the same collaboration in central production [18], but at an even higher mass of (1610 ± 20) MeV and a width of (170 ± 40) MeV. Evidence for this so–called $\mathrm{G}/f_0(1590)$ had first been reported in [19].

The experiment E760 at Fermilab [20] has reported the observation of an $\eta\eta$ resonance with mass and width $(m, \Gamma) = (1488 \pm 10, 148 \pm 17)$ MeV which are compatible with the properties observed for the $f_0(1500)$ in the present work.

In conclusion, the analysis of the high statistics data obtained on annihilation at rest, $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^0\eta\eta$ establishes the existence of two scalar isoscalar resonances with masses and widths in striking similarity to the masses and widths of two $\pi\pi$ scalar resonances recently observed in the same production process, i. e., in $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^0\pi^0\pi^0$ [1]. The observation of two resonances so close in mass supports the conjecture that non–$q\bar{q}$ objects exist in the 1–2 GeV mass range [21,22].

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