High-statistics study of $f_0(1500)$ decay into $\pi^0\pi^0$

Crystal Barrel Collaboration

C. Amsler[o], D.S. Armstrong[a 1], I. Augustin[h 2], C.A. Baker[e], B.M. Barnett[k], C.J. Batty[e], K. Beuchert[b], P. Birien[a], P. Blüm[h], R. Bossingham[a], K. Braune[l], J. Brose[k 3], D.V. Bugg[i], M. Burchell[f 4], T. Case[a], S.U. Chung[k 5], A. Cooper[i], O. Cramer[l], K.M. Crowe[a], T. Degener[b], H.P. Dietz[l], S. v. Dombrowski[o], M. Doser[f], W. Dünnweber[l], D. Engelhardt[h], M. Englert[l], M.A. Faessler[l], C. Felix[l], R. Hackmann[k], R.P. Haddock[j], F.H. Heinsius[a], M. Herz[k], N.P. Hessey[f], P. Hidas[d], P. Illinger[l], D. Jamnik[l 6], H. Kalinowsky[k], B. Kämmle[g], T. Kiel[h], J. Kisiel[l 7], E. Klempt[c], M. Kobel[f 8], H. Koch[b], C. Kolo[l], K. Königsmann[l 9], M. Kunze[b], M. Lakata[a], R. Landua[f], F. Loser[g], J. Lüdemann[b], H. Matthäy[b], M. Merkel[k 10], J.P. Merlo[k], C.A. Meyer[m], L. Montanet[f], A. Noble[o], F. Ould-Saada[o], K. Peters[b], C.N. Pinder[e], G. Pinter[d], S. Ravndal[b 10], C. Regenfus[l], J. Salk[b], E. Schäfer[k], P. Schmidt[g], R. Seibert[g], S. Spanier[k], H. Stöck[b], C. Straßburger[c], U. Strohbusch[g], M. Suffert[n], U. Thoma[c], D. Urner[o], C. Völcker[l], F. Walter[k], D. Walther[b], U. Wiedner[g], N. Winter[h], J. Zoll[f], B.S. Zou[i], Č. Zupančič[l]

[a] *University of California, LBL, Berkeley, CA 94720, USA*
[b] *Universität Bochum, D-44780 Bochum, FRG*
[c] *Universität Bonn, D-53115 Bonn, FRG*
[d] *Academy of Science, H-1525 Budapest, Hungary*
[e] *Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK*
[f] *CERN, CH-1211 Genève, Switzerland*
[g] *Universität Hamburg, D-22761 Hamburg, FRG*
[h] *Universität Karlsruhe, D-76021 Karlsruhe, FRG*
[i] *Queen Mary and Westfield College, London E1 4NS, UK*
[j] *University of California, Los Angeles, CA 90024, USA*
[k] *Universität Mainz, D-55099 Mainz, FRG*
[l] *Universität München, D-80333 München, FRG*
[m] *Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[n] *Centre de Recherches Nucléaires, F-67037 Strasbourg, France*
[o] *Universität Zürich, CH-8057 Zürich, Switzerland*

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The authors report a partial-wave analysis of the reaction $p\overline{p}\rightarrow\pi^0\pi^0\pi^0$ using a high-quality high-statistics data set of 712 000 events. In addition to the $f_0(975)$ and $f_0(1300)$, one further scalar resonance with mass $m = (1500 \pm 15)$ MeV and width $\Gamma = (120 \pm 25)$ MeV is necessary to describe the data.

[1] Now at College of William & Mary College, Williamsburg, VA 23187, USA
[2] Now at University of Siegen, Siegen, Germany
[3] This work comprises part of the Ph.D. thesis of J. Brose
[4] Now at University of Kent, Canterbury, UK
[5] Permanent address: BNL, Upton, NY
[6] On leave of absence from the University of Ljubljana, Ljubljana, Slovenia
[7] On leave of absence from the University of Silesia,

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Proton-antiproton annihilations at rest in liquid hydrogen favor the production of low spin meson resonances; recent analyses of these annihilations have provided new and important information on scalar resonances in particular[1–5]. It is well known that annihilation occurs primarily in S-states of protonium ($^1S_0$, $^3S_1$), yet an admixture of initial P-states cannot be excluded [6].

However, the first results obtained by the Crystal Barrel collaboration [7] with the analysis of 54 800 events of the totally symmetric annihilation channel

$$p\overline{p} \rightarrow 3\pi^0 \tag{1}$$

revealed the presence of a large $\pi^0\pi^0$ D-wave component associated mostly with initial $p\overline{p}$ P-states. This $\pi^0\pi^0$ D-wave was found to not only include the $f_2(1270)$ but also a 2^{++} resonance at $m = 1515\,\mathrm{MeV}$, identified as the 2^{++} AX resonance observed by the ASTERIX collaboration [8] in $p\overline{p} \rightarrow \pi^+\pi^-\pi^0$ from pure $p\overline{p}$ P-states. In [7], the $\pi^0\pi^0$ S-wave was constrained to follow the Au-Morgan-Pennington (AMP) [9] $\pi\pi$ S-wave scattering amplitude, i.e. a fixed coherent mixture of two resonances: the $f_0(975)$, also strongly coupled to the $K\overline{K}$ channel, and the broad $f_0(1300)$. The large amount of initial P-states ($\approx 60\%$) obtained with this analysis was unexpected. In a second attempt [5] a good description of the data was obtained using the N/D model [10] and imposing $p\overline{p}$ S-states only. In this re-analysis, the $\pi\pi$ S-wave AMP scattering amplitude constraint was relaxed and additional information from $p\overline{p}$ S-state annihilation in $p\overline{p} \rightarrow \eta\eta\pi^0$ data [1] was included. The latter annihilation channel is dominated by the presence of two $\eta\eta$ scalar resonances in the 1400-1600 MeV mass range. The N/D model used to parametrize the S-wave allows one to also take into account the effects due to the dynamics of the annihilation process. The main differences in the results with respect to [7] was that the contribution of the AX was reduced, and in addition to the expected $f_0(975)$ and $f_0(1300)$ resonances, a third $\pi\pi$ S-wave resonance was necessary at $m = 1520\,\mathrm{MeV}$, $\Gamma = 148\,\mathrm{MeV}$ to fit the data.

In this letter we present new data on the $3\pi^0$ Dalitz plot obtained with a much larger statistical sample (712 000 events) obtained with the Crystal Barrel detector at LEAR (CERN) in eight consecutive runs.

The experimental set up is described in [11]; the main component used to acquire the present data was the electromagnetic calorimeter consisting of 1380 CsI(Tl) crystals. The data on reaction (1) were extracted from 16.8 million events taken with an "all neutral" trigger which selects events with no charged tracks. The data were scanned for events with exactly six electromagnetic showers, which resulted in 3.2 million events. The two-photon invariant mass spectrum shows clear peaks due to the π^0, the η, and the η' with mass resolutions (before kinematic fitting) of 7.7 MeV, 16.7 MeV and 25.8 MeV, respectively. Out of these events, 1.4 million satisfied a four-constraint fit (with a confidence level exceeding 1%) imposing energy and momentum conservation. These data were subjected to a series of kinematic fits imposing the known masses of π^0, η and η'. We retained those events for which the χ^2 probability for the $3\pi^0$ hypothesis was larger than that of any other hypothesis and exceeds 10%. The fraction of $3\pi^0$ events in which the six photons can be combined to $3\pi^0$ in more than one way is less than 1%. All reactions which could contribute significantly to the 6γ final state were simulated using the Crystal Barrel Monte Carlo program based on the program package GEANT [12]. The Monte Carlo simulations show that the $3\pi^0$ data are practically free of background. The acceptance of the final state is nearly uniform over the whole $3\pi^0$ Dalitz plot with deviations not exceeding 2%, and the data set is corrected for these variations. The mean acceptance is $(30.2 \pm 0.1_{\mathrm{stat}} \pm 1.6_{\mathrm{syst}})\%$.

In the six photon final state we also find 5859 ± 92 $\omega\omega$ events. The signal strength is determined as described in [13]. We use the $\omega\omega$ branching ratio of [13] to determine that $BR(p\overline{p} \rightarrow 3\pi^0) = (6.2 \pm 1.0) \times 10^{-3}$.

Fig. 1 shows the $3\pi^0$ Dalitz plot. First, we qualitatively discuss its features. Due to the symmetry

Katowice, Poland
[8] Now at University of Freiburg, Freiburg i. Br., Germany
[9] Now at Max Planck Institut, Heidelberg, Germany
[10] Now at CERN, Genève, Switzerland

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Fig. 1. *The $\pi^0\pi^0\pi^0$ Dalitz plot.*

in the final state there are six entries per event. The highest intensities A reflect the interference of two of the three $f_2(1270)$ amplitudes for the reaction $p\overline{p} \rightarrow f_2(1270)\pi^0$. The $f_2(1270)$ decay angular distribution is peaked in the forward and backward directions. This is characteristic of a spin-2 particle produced from the ${}^1\mathrm{S}_0$ state of the $p\overline{p}$ atom. In the three corners a clear band B and an additional structure C are observed. The band around 1500 MeV suggests the existence of a meson decaying into two π^0's . The homogeneous population along the band suggests the quantum numbers 0^{++} . The structure C will be interpreted partly due to interferences of low-energy $\pi^0\pi^0$ S-wave interactions and partly due to a tensor resonance at 1540 MeV. The latter part of the interpretation is sensitive to the S/P ratio assumed for the initial states, whereas the evidence for the $f_0(1500)$ is not. Finally we notice a faint dip D approximately at the $K\overline{K}$ threshold.

The Dalitz plot is divided into 120×120 cells. For the fits, only one sextant of the Dalitz plot is used. This results in 1338 cells with nonzero entries. The reduced cell sizes at the sextant boundaries are accounted for. The total amplitude as defined below is calculated at 100 positions in each cell, averaged and compared to the experimental number in the cell by means of a χ^2 test. The CERN program package MINUIT [14] is used for the minimization. All fits presented here converged with an estimated distance to minimum below 10^{-5}.

The amplitudes for the partial-wave analysis are constructed in terms of the isobar model

$$A_{{}^{2S+1}\mathrm{L}_J}(\boldsymbol{p},\boldsymbol{q}) = \sum Z_{{}^{2S+1}\mathrm{L}_{J,L,l}}(\boldsymbol{p},\boldsymbol{q})\; F^l(q)\; B^L(p) \quad (2)$$

The initial $p\overline{p}$ state is characterized by the quantum numbers ${}^{2S+1}\mathrm{L}_J$, and the final state is characterized by the quantum numbers L, l. L is the angular momentum between the isobar and the recoil meson of momenta $\pm\boldsymbol{p}$, and l is the angular momentum of the isobar splitting into two mesons of center-of-mass momenta $\pm\boldsymbol{q}$. For two π^0's , l must be even; we further restrict $l = 0$ or 2. Hence the isobar can only have $J^{PC} = 0^{++}$ or $J^{PC} = 2^{++}$. Note that selection rules allow $p\overline{p}$ annihilation into $\pi^0\pi^0\pi^0$ to proceed exclusively via the ${}^1\mathrm{S}_0$,${}^3\mathrm{P}_1$ and ${}^3\mathrm{P}_2$ states since D-state capture is negligible (see [15]). In the following analysis, the three possible initial states will be included unless otherwise specified.

The angular distributions are described by spin-parity functions $Z_{{}^{2S+1}\mathrm{L}_{J,L,l}}$ as given by Zemach [16]. The angular-momentum barrier factor B^L can be found in [3,17]. Different hypotheses are investigated for the dynamical functions $F^l(q)$.

In this analysis, two-body unitarity conservation is guaranteed by a systematic use of the K-matrix formalism, and the possibility that the $\pi\pi$ scattering amplitude may be modified by the production process is taken into account with the introduction of a P-vector [18] as explained below.

We define the dynamical function F as

$$F = (I - iK\rho)^{-1}P, \quad (3)$$

namely the product of the propagator $(I - iK\rho)^{-1}$ (I is the identity matrix and ρ is the two-body phase space) and the production vector P [17]. Note that ρ is imaginary below the associated threshold. 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 (real) couplings $g_{\alpha i}$:

$$P_i \;=\; \sum_\alpha \frac{\beta_\alpha\; g_{\alpha i} B_i^l}{m_\alpha^2 - m^2}. \quad (4)$$

The coupling of different channels is achieved by an appropriate choice of a K-matrix

$$K_{ij}(m) \;=\; \sum_\alpha \frac{g_{\alpha i} g_{\alpha j} B_i^l B_j^l}{m_\alpha^2 - m^2} + C_{ij}, \quad (5)$$

$$g_{\alpha i} \;=\; \sqrt{\frac{m_\alpha \tilde{\Gamma}_{\alpha i}}{\rho_i(m_\alpha)}}, \quad (6)$$

C_{ij} being real constants. We recall here that K-matrix poles are not Breit-Wigner poles. The $\tilde{\Gamma}_{\alpha i}$ in our case cannot be identified with partial widths of resonances, since no data on the second channel $(K\overline{K})$ were available .

We guarantee that the $\pi\pi$ S-wave scattering amplitude goes to zero near threshold by introducing a factor $(m^2 - 2m_\pi^2)/m^2$ in front of (5). The K-matrix is related to the scattering amplitude T by

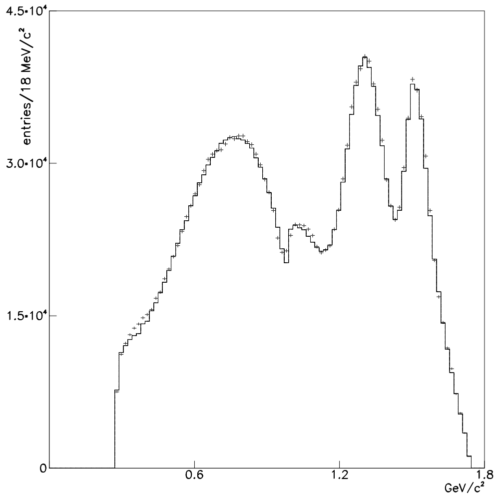

Fig. 2. *The $\pi^0\pi^0$ invariant mass distribution. The solid line represents the fit.*

$$T = (I - iK\rho)^{-1}K. \tag{7}$$

The T-matrix (7) and the dynamical amplitude F (3) are connected via the K-matrix (5). This allows us to fit the Crystal Barrel data simultaneously with $\pi\pi$ scattering data [19,20]. Since we find new resonances in the mass range above 1.2 GeV, we use the scattering data only for $\pi\pi$ masses below this value. In this mass range the $\pi\pi$ scattering data are compatible with the results of our fits. Above 1.2 GeV we allow for additional poles in the K-matrix. Thus we ensure that the amplitudes preserve unitarity and analyticity. Since we observe a strong effect of the $K\overline{K}$ threshold in the data we use a 2×2 K-matrix with $\pi\pi$ as the first channel and $K\overline{K}$ as the second. For higher masses, $K\overline{K}$ is used to parameterize any inelasticity. Altogether, 34 free parameters are used in the fit described below.

A minimum of three poles in the $\pi\pi$ S-wave and of two poles in the $\pi\pi$ D-wave is required to obtain a good fit with $\chi^2/N_F = 2028/(1338-34) = 1.6$. The χ^2/N_F is larger than unity; however no systematic deviations between data and fit can be found in the Dalitz plot or in the invariant mass spectrum and angular distributions (fig. 2, 3). The results of the fit are given in tables 1 and 2. Quoted errors are pure MINUIT errors and do not reflect the results of systematic variations of the fit parameters.

	mass (MeV)	$\tilde{\Gamma}_{\pi^0\pi^0}$ (MeV)	$\tilde{\Gamma}_{K\overline{K}}$ (MeV)
S_1	855 ± 7	774 ± 38	0 ±
S_2	1268 ± 32	1311 ± 168	72 ± 25
S_3	1493 ± 13	14 ± 3	116 ± 17
D_1	1246 ± 8	188 ± 23	
D_2	1547 ± 9	139 ± 16	
$c_{11} = c_{22} = 0$			$c_{12} = 0.78 \pm 0.05$

Table 1
K-matrix parameters for $\pi\pi$ S-wave and $\pi\pi$ D-wave. c contains the coefficients of the 2×2 S-wave K-matrix.

		$\lvert\beta_\alpha\rvert$	arg (β_α) (radians)
$^1\mathrm{S}_0$	S_1	-0.14 ± 0.01	—
	S_2	0.15 ± 0.02	3.1 ± 0.1
	S_3	-1.06 ± 0.20	-5.9 ± 0.2
	D_1	0.20 ± 0.03	3.8 ± 0.2
	D_2	-0.36 ± 0.05	2.3 ± 0.2
$^3\mathrm{P}_1$	S_1	0.04 ± 0.01	—
	S_2	-0.07 ± 0.03	10.6 ± 0.8
	S_3	0.66 ± 0.20	5.3 ± 0.7
	D_1	-0.35 ± 0.09	2.0 ± 0.4
	D_2	0.35 ± 0.09	13.0 ± 1.0
$^3\mathrm{P}_2$	D_1	-0.33 ± 0.08	—
	D_2	-0.29 ± 0.10	-10.6 ± 1.0

Table 2
Production parameters.

Mass and width of the first $\pi\pi$ S-wave K-matrix pole were determined from the speed plot d$|T|$/dm. One finds m = 994 ± 5 MeV and Γ = 26 ± 10 MeV. Therefore it can be identified as the $f_0(975)$ [21].

The second $\pi\pi$ S-wave K-matrix pole corresponds to T-matrix poles which are very close on both Riemann sheets and which yield resonance parameters $m = 1330\,\mathrm{MeV}$, $\Gamma = 760\,\mathrm{MeV}$, which allow to identify it as the $f_0(1300)$ [21]. A reliable determination of the inelasticity is not possible when using the $3\pi^0$ data only.

The third $\pi\pi$ S-wave K-matrix pole corresponds again to T-matrix poles very close to each other on the second and third Riemann sheets, providing evidence for a new resonance, which we call $f_0(1500)$ (although, strictly speaking, its isospin

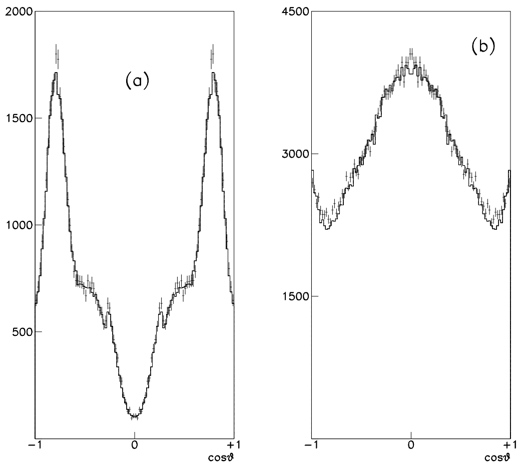

Fig. 3. *Angular distributions around the $K\overline{K}$ threshold (a) and around 1500 MeV (b). The solid line represents the fit.*

may be $I = 0$ or $I = 2$ as long as we limit our observation to the $\pi^0\pi^0$channel). The values of the mass, width and production rate of this resonance in the $3\pi^0$ final state are

$$\begin{aligned} m &= (1490 \pm 13)\,\mathrm{MeV}, \\ \Gamma &= (120 \pm 15)\,\mathrm{MeV}, \\ BF &= (12 \pm 2)\%. \end{aligned}$$

The inelasticity of the $f_0(1500)$ [and that of the $f_0(1300)$] cannot be reliably determined from the observation of the $3\pi^0$ data alone. If the third $\pi\pi$ S-wave K-matrix pole is not introduced, the fit deteriorates by $\Delta\chi^2 = 600$.

The two $\pi\pi$ D-wave K-matrix poles (in this case the K-matrix is reduced to a single channel K-number) correspond to T-matrix poles which can be identified as the $f_2(1270)$ with $m = 1285$ MeV and $\Gamma = 195$ MeV, and as the $f_2(1520)/AX$ [21,8] with $m = 1530$ MeV, $\Gamma = 135$ MeV.

By integrating the production strengths of the $\pi\pi$ S-wave [excluding $f_0(1500)$], the $f_0(1500)$ itself and the $\pi\pi$ D-waves [$f_2(1275)$ and $f_2(1520)$] over the Dalitz plot, and appropriately renormalizing, the fractional contributions to the $3\pi^0$ annihilation channel are

$$\begin{aligned} f_0(975) + f_0(1300) &: 42\% \\ f_0(1500) &: 12\% \\ f_2(1275) &: 29\% \\ f_2(1520) &: 17\%. \end{aligned}$$

All these results are in good agreement with [5]. In particular, three scalar and two tensors resonances are needed in both analyses, although the two approaches use quite different methods and assumptions. Most notably, the present fit is obtained using a substantial $p\overline{p}$ P-state contribution. Integrating the various contributions to this fit over the Dalitz plot, we find that $^1\mathrm{S}_0$, $^3\mathrm{P}_1$ and $^3\mathrm{P}_2$ initial states contribute 54%, 29% and 17%, respectively, whereas [5] assumes 100% $^1\mathrm{S}_0$. As expected in the present fit, most of the P-state contribution is related to the production of $\pi\pi$ D-wave, but we also find that $^3\mathrm{P}_1$contributes about 20% of the $f_0(1500)$ production. To clarify the influence of the P-state contribution, we have repeated the analysis, imposing a pure $^1\mathrm{S}_0$ initial state, as in [5]. The quality of the fit deteriorates drastically, $\chi^2/N_F = 2604/(1338 - 25) = 2$, even with the introduction of four poles in the K-matrix for the $\pi\pi$ S-wave. Nevertheless, this fit still requires a pole in the vicinity of 1500 MeV.

Following the N/D method [10], it is also possible to obtain another equally good interpretation of the high-statistics data of reaction (1). Imposing a pure $^1\mathrm{S}_0$ initial state and using now the full sample of $3\pi^0$ data, but not combining it with $p\overline{p} \to \eta\eta\pi^0$ data [1] as was done in [5], we obtain a χ^2 of $2104/(1338 - 30) = 1.6$. Again, we need to introduce a scalar resonance in the 1500 MeV region into the fit, with $m = (1505 \pm 8)$ MeV, $\Gamma = (132 \pm 14)$ MeV and $BF(p\overline{p} \to f_0(1500)\pi^0/p\overline{p} \to 3\pi^0) = (12 \pm 2)\%$.

Thus, regardless of the various fractions of $p\overline{p}$ P-states assumed in the different analyses, one can conclude that the $f_0(1500)$ is present in reaction (1). A more accurate partial-wave analysis will be possible once we are able to experimentally modify the $p\overline{p}$ S/P ratio, e.g. by accumulating data on reaction 1 with a gaseous hydrogen target.

For the sake of completeness, we also repeated the analysis, using the formalism applied in [7], i.e. imposing that the $\pi\pi$ S-wave follows the AMP [9] parameterization below 1300 MeV. The fit is not nearly as good as the previous ones (using the P-vector or the N/D method), $\chi^2/N_F = 2658/(1338-23) = 2$. The main discrepancy between this fit and data can be traced back to the $\pi\pi$ mass spectrum around the $K\overline{K}$ threshold region, and not around 1500 MeV, where a scalar resonance has to been introduced with $m = (1498 \pm 11)$ MeV, $\Gamma = (98 \pm 19)$ MeV. In this fit the initial P-state fraction is found to be 42%. Without this scalar resonance, the fit vastly deteriorates ($\chi^2/N_F = 3905/(1338-17) = 3$).

Finally, we also note that another equally good fit can be obtained using the P-vector approach described above, with the introduction of an additional K-matrix pole. The main consequence is the replacement of the $f_0(1300)$ by both a narrower resonance with $m = (1330 \pm 50)$ MeV, $\Gamma = (300 \pm 80)$ MeV and also a $\pi\pi$ S-wave background centred around 1100 MeV and ranging over 500 to 700 MeV. This 4-pole interpretation of the $\pi\pi$ S-wave is in closer agreement with our own findings [2,5] and also with a recent re-analysis of the $\pi\pi$ S-wave [22]. However, this does not affect our conclusions on the $f_0(1500)$, which remains present within the errors given below.

In conclusion, all approaches made to analyze the high statistics data obtained with the Crystal Barrel detector on $p\overline{p} \to 3\pi^0$ require the presence of a scalar resonance in the 1500 MeV mass region. Taking into account the spread of the masses, widths and production rates obtained with various acceptable fits, we estimate that the characteristics of this $f_0(1500)$ as observed in $p\overline{p} \to 3\pi^0$ are the following:

$$
\begin{aligned}
m &= (1500 \pm 15)\,\mathrm{MeV} \\
\Gamma &= (120 \pm 25)\,\mathrm{MeV} \\
BF &= (13 \pm 4)\%
\end{aligned}
$$

For the branching fraction (BF) in liquid hydrogen, we use the rate $BF(p\overline{p} \to 3\pi^0) = (6.2 \pm 1.0) \times 10^{-3}$, given above. Table 3 gives a summary of the fits discussed in this letter.

The masses and widths of a resonance near 1500 MeV found in both $\eta\eta$ decay [1,5] and in $\eta\eta'$ decay [26] agree with the values for the $f_0(1500)$ presented herein. Assuming that we are observing three decay modes ($\pi\pi$, $\eta\eta$, $\eta\eta'$) of the same object, a measurement of the relative branching

Analysis	mass (MeV)	Γ (MeV)	BF (%)
3 pole P-vector	1490 ± 13	120 ± 15	12 ± 2
N/D	1505 ± 8	132 ± 14	12 ± 2
AMP	1498 ± 11	98 ± 19	12 ± 2
4 pole P-vector	1490 ± 10	115 ± 15	17 ± 2
OUR ESTIMATE	1500 ± 15	120 ± 25	13 ± 4
Crystal Barrel [5]	1520 ± 25	148^{+20}_{-25}	–
E760 [23]	1488 ± 10	148 ± 17	–

Table 3
Results from this analysis and from other analyses. Our estimate also includes systematic variations in the fit procedures.

ratios can be evaluated, using the full samples of data accumulated by the Crystal Barrel Collaboration on $p\overline{p} \to \pi^0\pi^0\pi^0$, $\eta\eta\pi^0$ and $\eta\eta'\pi^0$. Results of this analysis will be presented in a forthcoming publication. The mass and width of the $f_0(1500)$ agree very well with the values found in the experiment E760 at Fermilab in $p\overline{p}$ annihilation in flight with $\overline{p}$ momenta of 3–4 GeV/c [23], yet no partial wave analysis has been carried out on that data. The $f_0(1500)$ cannot be identified with the $s\overline{s}$ meson observed by the LASS collaboration [24]; otherwise it should have been observed in $p\overline{p}$ annihilation in the $K\overline{K}\pi$ final state, but such has not been the case [25].

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