$\eta\eta'$ threshold enhancement in $\bar{\rm p}$p annihilations into $\pi^0\eta\eta'$ at rest

Crystal Barrel Collaboration

C. Amsler[o], D.S. Armstrong[a1], I. Augustin[h2], 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], D.V. Bugg[i], M. Burchell[f3], T. Case[a], S.U. Chung[k4], A. Cooper[i], 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[k5], R.P. Haddock[j], F.H. Heinsius[a], M. Herz[k], N.P. Hessey[f], P. Hidas[d], P. Illinger[l], D. Jamnik[l6], H. Kalinowsky[k], B. Kämmle[g], T. Kiel[h], J. Kisiel[l7], E. Klempt[c], M. Kobel[f8], H. Koch[b], C. Kolo[l], K. Königsmann[l9], M. Kunze[b], M. Lakata[a], R. Landua[f], F. Loser[g], J. Lüdemann[b], H. Matthäy[b], M. Merkel[k10], 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[b10], J. Salk[b], E. Schäfer[k], P. Schmidt[g], S. Spanier[k], C. Straßburger[c], U. Strohbusch[g], M. Suffert[n], 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-76344 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, USA*
[n] *Centre de Recherches Nucléaires, F-67037 Strasbourg, France*
[o] *Universität Zürich, CH-8057 Zürich, Switzerland*

Received ; revised manuscript received

We report on the observation of an $\eta\eta'$ threshold enhancement produced in $\bar{\rm p}$p annihilations at rest into $\pi^0\eta\eta'$, which we identify with the recently discovered $f_0(1500)$.

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

In a recent letter we have reported on the observation of a new scalar meson, the $f_0(1500)$ with a mass of (1520 ± 25) MeV and a width of (148 ± 25) MeV decaying into $\pi^0\pi^0$ and $\eta\eta$ [1]. Moreover, a scalar meson called G/$f_0(1590)$, at a slightly higher mass and larger width, had been observed previously in the $\eta\eta$ and $\eta\eta'$ final states [2,3] with a mass and width of (1568 ± 33) MeV and (260 ± 60) MeV as measured in $\eta\eta'$ decay. The large coupling to $\eta\eta'$ was surprising ($\Gamma(G/f_0(1590)\rightarrow \eta\eta')/\ \Gamma(G/f_0(1590)\rightarrow \eta\eta) = 2.7 \pm 0.8$) and was interpreted as evidence of a glueball nature for this state [4]. These facts motivated us to search for the reaction $\bar{\rm p}{\rm p} \rightarrow \pi^0\eta\eta'$ with the Crystal Barrel Detector at the CERN Low Energy Antiproton Ring (LEAR) by stopping 200 MeV/c antiprotons in a liquid hydrogen target. Details on the detector are given elsewhere [5].

We have chosen the six–photon final state to search for $\pi^0\eta\eta'$ with all three pseudoscalar mesons decaying into two photons. This choice limits the photon–combinatorics (compared to decay modes like $\eta'\rightarrow\pi^0\pi^0\eta$), but reduces the statistics, as the η' decay branching ratio into two photons is only 2.12%. A total of 16.8×10^6 annihilations were recorded, using a "zero prong trigger", i.e. requiring that an antiproton should enter and not leave the target, and that no charged particles be detected in the charged track detectors surrounding the target [5]. After removing events with residual track elements we keep 15×10^6 "all neutral" annihilations corresponding to about 4×10^8 $\bar{\rm p}{\rm p}$ annihilations. There are 3.2×10^6 events with exactly six electromagnetic showers. This sample is further reduced to 1.4×10^6 events when a 4C kinematic fit –imposing energy and momentum conservation– is applied to the $\bar{\rm p}{\rm p} \rightarrow 6\ \gamma$ hypothesis (probability $> 1\%$).

The remaining sample is subjected to a series of kinematic fits in which the meson masses are imposed in addition to energy and momentum conservation ($\pi^0\pi^0\gamma\gamma$, $\pi^0\eta\gamma\gamma$ (6C); $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta'$, $\pi^0\eta\eta'$ (7C); $\omega\omega$(8C)). Events for which the confidence level for one of these hypotheses (except $\pi^0\eta\gamma\gamma$ or $\pi^0\eta\eta'$) is larger than 1% are rejected. We show in Fig. 1 the $\gamma\gamma$ invariant mass distribution for the events compatible with a 6C fit to the $\pi^0\eta\gamma\gamma$ hypothesis with a confidence level exceeding 10%. A clear signal is observed at ≈ 955 MeV . This indicates the presence of the $\eta'(958)$.

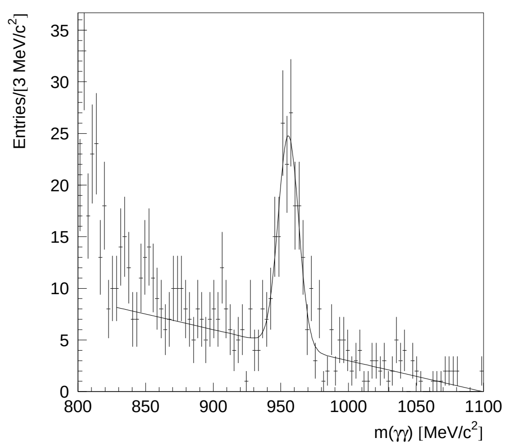

Fig. 1. *The $\gamma\gamma$ invariant mass of the remaining γ–pair in $\pi^0\eta\gamma\gamma$ of the untriggered data set. A gaussian function with a linear background term is superimposed.*

To estimate quantitatively the size of this signal, we fit to the distribution a gaussian function superimposed on a linear background. The central mass value is found to be at (955.6 ± 0.6) MeV with $\sigma = (7.6 \pm 0.7)$ MeV .

The signal contains (130 ± 14) events. A 7C kinematic fit, corresponding to the $\pi^0\eta\eta'$ hypothesis for the events falling in the mass window $900\,\text{MeV} \leq\ m_{\gamma\gamma} \leq 1020\,\text{MeV}$, leaves 158 events satisfying this hypothesis with a confidence level larger than 10%. This is the sample of "zero prong trigger" events which will be used in the following analysis. From the size of the signal observed on the Fig. 1, we conclude that this sample includes a background contribution of the order of 41 events expected to pass the 7C fit.

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

The efficiency of the data selection and identification of the $\pi^0\eta\eta'$ channel in the six–photon final state is 15.9% as determined by Monte Carlo, assuming a flat phase space distribution for $\pi^0\eta\eta'$. The selection and reconstruction efficiency of the $\pi^0\eta\eta'$ events is uniform over the Dalitz–plot. Scaling the number of observed events with the number of events attributed to $\bar{p}p \rightarrow \omega\omega$, for which the annihilation branching fraction has been determined in [6], and using the two–photon branching ratios [7], we arrive at the annihilation branching fraction :

$$\mathrm{BR}(\bar{p}p \rightarrow \pi^0\eta\eta') = (\ 2.5 \pm 0.5\ ) \cdot 10^{-4}\ .$$

We have studied possible background contributions with Monte Carlo simulations.These Monte Carlo events are produced assuming phase space distribution and analysed with the same analysis chain as real data. Backgrounds are found to come from $\pi^0\eta\eta$ (6 events) and $\pi^0\eta\omega$ (15 events), leaving ≈ 20 background events unexplained.

Some events of the type $\pi^0\pi^0\pi^0$ that fail the $\pi^0\pi^0\pi^0$ (7C hypothesis), happen to satisfy the kinematics for the process $\pi^0\eta\gamma\gamma$ with a $\gamma\gamma$ invariant mass close to the η' mass. This background is completely eliminated by the $\pi^0\pi^0\gamma\gamma$ rejection.

In order to improve the statistics for the $\pi^0\eta\eta'$ channel, we have set up a special trigger enhancing the fraction of $\bar{p}p \rightarrow 6\ \gamma$ events which correspond to the $\pi^0\eta\eta'$ channel. The hardware trigger requires the absence of tracks from charged particles in the drift chamber and the detection of 5 to 7 photons in the calorimeter. A fast on–line reconstruction program selects events having exactly six photons and calculates the two–photon invariant masses (with 15 combinations per event). Events are accepted when the six photons can be combined to form one π^0, one η and one η' meson. When real data are processed with the trigger program $\approx 85\%$ of the events which are identified as $\pi^0\eta\eta'$ events in the analysis chain are accepted. When triggered data undergo the same analysis chain as the "zero prong trigger" events, 819 candidates are found. The triggered data show the same characteristics as the untriggered data. Fits to the two individual Dalitz–plots give completely compatible results. We therefore combine the two sets of data, i.e. a total of 977 events

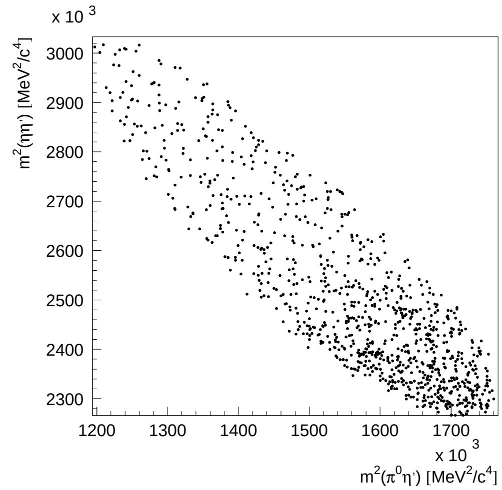

Fig. 2. *The $\pi^0\eta\eta'$ Dalitz–plot of the combined data set.*

(which include a flat incoherent background of ≈ 254 events), in the following analysis.

Fig. 2 shows the $\pi^0\eta\eta'$ Dalitz–plot and Fig. 3 the $\eta\eta'$ mass projection and the decay angular distribution of the $\eta\eta'$ system.

There is a strong enhancement in the lower right corner of the Dalitz–plot.This enhancement might *a priori* be attributed to the $\pi^0\eta'$ decay mode of the $a_2(1320)$ or to an $\eta\eta'$ resonance. In the $\pi^0\eta\eta$ final state we do not observe evidence for $\bar{p}p \rightarrow \eta a_2$, $a_2 \rightarrow \pi^0\eta$. From the known $a_2 \rightarrow \pi\eta'$ decay branching ratio [7] we estimate that the channel $\bar{p}p \rightarrow \eta a_2\ a_2 \rightarrow \pi^0\eta'$ contributes less than 30 events to the combined data set. Hence this reaction cannot be responsible for the mass enhancement and we conclude that we observe an $\eta\eta'$ effect. The mass range might suggest that we are dealing with the $f_2'(1525)$ resonance, but again the production rate is known to be too small [8] to allow this interpretation. Furthermore, the angular distribution in the $\eta\eta'$ rest frame is flat (see Fig. 3) in this region.

We have also observed this enhancement in a different final state: the channel $\bar{p}p \rightarrow \pi^0\eta\eta'$was also studied for η' decaying to $\eta\pi^+\pi^-$ (final state $\pi^+\pi^-\eta\eta\pi^0$, leading to $\pi^+\pi^-\ 6\gamma$).

Events with two charged tracks reaching the outer layers of the jet drift chamber were submitted to an online hardwired processor selecting eight clusters in the barrel. An online software trigger then computed all combinations of two-cluster invariant masses and required two η's and one π^0. Events consistent with $\pi^0\eta\eta'$ were then selected in the offline analysis by applying a suitable cut in the $\eta\pi^+\pi^-$ mass distribution around the η' peak. The Dalitz–plot is identical to the one presented in Fig. 2 and the $\eta\eta'$ mass distribution for the resulting 404 events is shown in Fig. 4.

Thus we attempt to describe the Dalitz–plot (see Fig. 2) with two amplitudes, a relativistic Breit–Wigner amplitude $BW(\eta\eta')$ for production of a scalar resonance decaying into $\eta\eta'$ and a flat incoherent background. Assuming S-wave dominance in liquid hydrogen, the only initial atomic state to be considered here is $^1\mathrm{S}_0$. We use the Breit–Wigner amplitude in the following form

$$BW(\eta\eta') = \frac{m_0\Gamma_0}{m_0^2 - m^2 - im_0\Gamma(m)} \tag{1}$$

with

$$\Gamma(m) = \Gamma_0 \frac{m_0}{m}\frac{q}{q_0}, \tag{2}$$

where q is the breakup momentum and m_0 the resonance mass. The total amplitude squared is then given by

$$|\mathcal{A}|^2 = \left|\sqrt{a}\frac{BW(\eta\eta')}{\sqrt{\int |BW(\eta\eta')|^2 d\Omega}}\right|^2 + \left|\sqrt{N_{exp}-a}\frac{1}{\sqrt{\int d\Omega}}\right|^2 \tag{3}$$

The amplitude contains three parameters, two for the Breit–Wigner $BW(\eta\eta')$ and a, the number of the true $\pi^0\eta\eta'$ events. The fit finds that a (flat, incoherent) background of (296 ± 50) events is present in the sample, in agreement with the estimation made above (254 events) . Adding coherently to the first term of (3) an $\eta'\pi$ S-wave resonance with mass and width (1450,270) MeV as those measured by us [10] for the $a_0(1450)$ in $\bar{\mathrm{p}}\mathrm{p} \to \eta\pi^0\pi^0$ does not result in an improvement of the fit and does not yield any significant contribution for this $a_0(1450)$. It will therefore not be included in the following results. Due to the low statistics, a maximum likelihood method is chosen to fit the data. We minimize the negative log likelihood function:

$$-\ln\mathcal{L} = \int |\mathcal{A}|^2\, d\Omega - \sum_{i=1}^{N_{exp}} \ln(|\mathcal{A}_i|^2) \tag{4}$$

where the summation extends over the data points. The amplitudes are normalized over the Dalitz–plot in every iteration of the fit. With this normalisation $\int |\mathcal{A}|^2\, d\Omega = N_{exp}$.

The fit is shown as a solid line in Fig. 3 and reproduces reasonably well the experimental distributions. A χ^2-test on these distributions yields a value of χ^2=54 for 40 bins. In comparison, assuming that the threshold enhancement is a tensor resonance results in an unacceptable χ^2 of 277 .

From the fit we obtain a mass of $M_X = (1545 \pm 25)$ MeV and a width of $\Gamma_X = (100 \pm 40)$ MeV. The errors are estimated from variations of the background parametrisation. A total of (681 ± 50) events is assigned to the $\eta\eta'$ resonance. This corresponds to a combined branching fraction of

$$\mathrm{BR}(\bar{\mathrm{p}}\mathrm{p} \to \pi^0 X, X \to \eta\eta'\,) = (1.7 \pm 0.4) \cdot 10^{-4}$$

Describing the $\eta\eta'$ threshold enhancement with a 2×2–K–matrix, with $\eta\eta$ as the second channel, does not significantly modify these conclusions.

As the observed enhancement occurs near the $\eta\eta'$ threshold, we also tried to interpret the data in terms of an $\eta\eta'$ scattering length. The data were fitted using

$$L(\eta\eta') = \frac{1}{1 - a_0 p_{\eta\eta'}} \tag{5}$$

instead of the Breit–Wigner amplitude in eq. (3), p being the three momentum of the η in the $\eta\eta'$system. The χ^2 increases to 73 and the deterioration can be traced to the $\eta\eta'$ threshold region. The scattering length is determined to be $a_0 = (1.75 \pm 0.20)$ fm. Due to the large χ^2 we do not find this solution acceptable.

We finally note that in these annihilations at rest, the total energy of the π^0 is small and may, at most, reach 330 MeV; we have therefore tried to introduce an amplitude which would take into account the effects due to the emission of the soft pion. Assuming the dominance of One Nucleon Exchange [9], we parametrize the intensity as follows:

$$I_{sp} = \frac{1}{E_{\pi^0}^2}\left(\frac{\boldsymbol{p}_\eta \boldsymbol{p}_{\pi^0}}{2m_N E_\eta - m_\eta^2} + \frac{\boldsymbol{p}_{\eta'} \boldsymbol{p}_{\pi^0}}{2m_N E_{\eta'} - m_{\eta'}^2}\right)^2 \quad (6)$$

where p_π is the 3-momentum of the pion and E_π its energy. This minimal distortion alone is not sufficient to reproduce the observed threshold enhancement ($\chi^2 = 112$).

In conclusion, we have observed an $\eta\eta'$ threshold enhancement in the reaction $\bar{\rm p}{\rm p} \rightarrow \pi^0\eta\eta'$. The most likely interpretation is that it is another decay mode of the $f_0(1500)$ resonance observed in $\bar{\rm p}{\rm p} \rightarrow f_0\ \pi^0$, $f_0 \rightarrow \pi^0\pi^0$ and $\bar{\rm p}{\rm p} \rightarrow f_0\ \pi^0$, $f_0 \rightarrow \eta\eta$ [1]. Its mass and width found in this analysis are (1545$\pm$25) MeV and (100$\pm$40) MeV respectively.

The measurement of the branching ratios of this $f_0(1500)$ resonance into $\pi\pi$,$\eta\eta$ and $\eta\eta'$ is being evaluated, making use of the full samples of data accumulated by the Crystal Barrel Collaboration on $\bar{\rm p}{\rm p} \rightarrow \pi^0\pi^0\pi^0$, $\bar{\rm p}{\rm p} \rightarrow \eta\eta\pi^0$ and $\bar{\rm p}{\rm p} \rightarrow \eta\eta'\pi^0$, and will be presented in a forthcoming publication.

The value obtained for the mass is not incompatible with the value obtained by GAMS for the $\eta\eta'$ decay mode of the G/$f_0(1590)$. The value obtained for the width, however, differs significantly.

Acknowledgement

We would like to thank the technical staff of the LEAR machine group and of all the participating institutions for their invaluable contributions to the success of the experiment. We acknowledge financial support from the German Bundesministerium für Forschung und Technologie, the Schweizerischer Nationalfonds, the British Science and Engineering Research Council and the US Department of Energy (contract No. DE-FG03-87ER40323 and DE-AC03-76SF00098). S.U. Chung, F.H. Heinsius and J. Kisiel benefit from financial support provided by the Alexander von Humboldt Foundation. The Mainz group likes to thank B. Renk for the maintenance of their local computer cluster.

References

[1] V. Anisovich et al. (Crystal Barrel Collaboration),

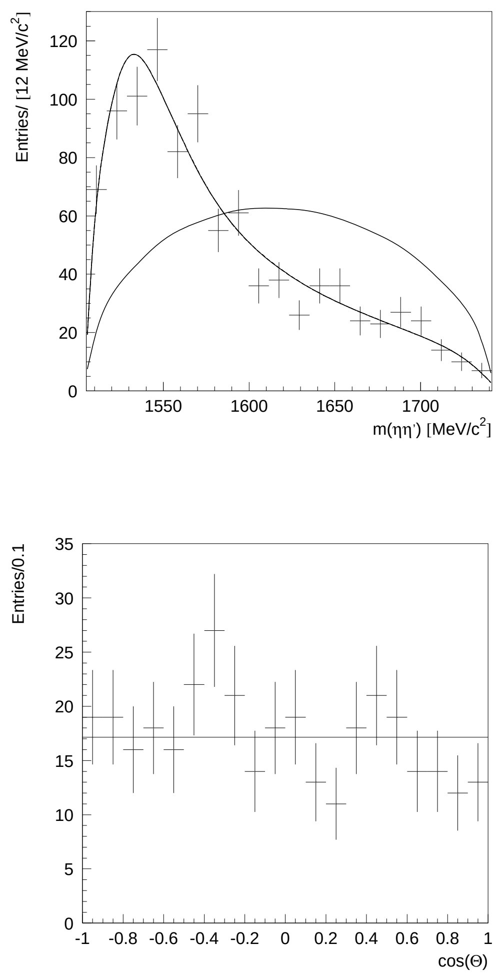

Fig. 3. *The $\eta\eta'$ projection with fit superimposed (full line) and assuming pure phase space (dotted line). The lower figure shows the angular distribution along an $\eta\eta'$ mass band of* 1546 ± 20 *MeV.*

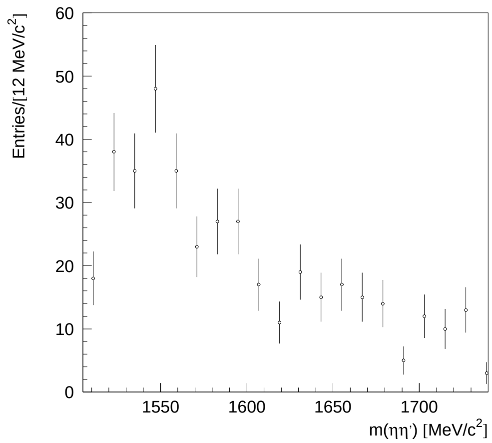

Fig. 4. *The $\eta\eta'$ projection derived from the reaction $\bar{p}p \to \pi^+\pi^-\eta\eta\pi^0$ exhibits the same features as the $\eta\eta'$ spectrum in Fig.3.*

Phys. Lett. **B323**(1994)233

[2] D. Alde et al. (GAMS Collaboration), Phys. Lett. **B201**(1988)160

[3] F. G. Binon et al. (GAMS Collaboration), Nuovo Cimento **80A**(1984)363

[4] S. S. Gershtein et al., Z. Phys. C – "Particles and Fields" **24**(1984)305

[5] E. Aker et al. (Crystal Barrel Collaboration), Nucl. Instrum. Methods **A321**(1992)69

[6] C. Amsler et al. (Crystal Barrel Collaboration) Z. Phys. C – "Particles and Fields" **42**(1993)175

[7] Review of Particle Properties , Phys.Rev. **D50**(1994)

[8] L. Gray et al. Phys. Rev. **D27** (1983) 307

[9] A.Grigoryan. Private communication

[10] C.Amsler et al. (Crystal Barrel Collaboration) Phys. Lett. B333 (1994) 277