Recent results in light meson spectroscopy from low-energy $\bar{p}p$ annihilations

N.P. HESSEY on behalf of the CRYSTAL BARREL COLLABORATION:

C. Amsler[15], D. S. Armstrong[1], C.A. Baker[5], B.M. Barnett[11], C.J. Batty[5], K. Beuchert[2], P. Birien[1], P. Blüm[8], R. Bossingham[1], K. Braune[12], J. Brose[11], D.V. Bugg[9], T. Case[1], A. Cooper[9], O. Cramer[12], K.M. Crowe[1], T. Degener[2], H.P. Dietz[12], S. von Dombrowski[15], M. Doser[6], W. Dünnweber[12], D. Engelhardt[8], M. Englert[12], M.A. Faessler[12], C. Felix[12], R. Hackmann[12], R.P. Haddock[10], F.H. Heinsius[1], M. Herz[11], N.P. Hessey[12], P. Hidas[4], P. Illinger[12], D. Jamnik[12,a], H. Kalinowsky[11], B. Kämmle[7], T. Kiel[7], J. Kisiel[12], E. Klempt[3], M. Kobel[6], H. Koch[2], C. Kolo[12], M. Kunze[2], M. Lakata[1], R. Landua[6], F. Loser[7], J. Lüdemann[2], H. Matthaey[2], R. McCrady[13], J.P. Merlo[11], C.A. Meyer[13], L. Montanet[6], A. Noble[15], F. Ould-Saada[15], K. Peters[2], C.N. Pinder[5], G. Pinter[4], S. Ravndal[2], C. Regenfus[12] J. Salk[2], E. Schäfer[11], P. Schmidt[7], S. Spanier[11], C. Straßburger[3], U. Strohbusch[7], M. Suffert[14], D. Urner[15], C. Völcker[12], F. Walter[11], D. Walther[2], U. Wiedner[7], N. Winter[8], J. Zoll[6], B. Zou[9], Č. Zupančič[12]

[1] *University of California, LBL, Berkeley, CA 94720, USA*
[2] *Universität Bochum, D-44788 Bochum, Germany*
[3] *Universität Bonn, D-53115 Bonn, Germany*
[4] *Academy of Science, H-1525 Budapest, Hungary*
[5] *Rutherford Appleton Laboratory, Chilton, Didcot OX11, 0QX UK*
[6] *CERN, CH-1211 Genève, Switzerland*
[7] *Universität Hamburg, D-22761 Hamburg, Germany*
[8] *Universität Karlsruhe, D-76344 Karlsruhe, Germany*
[9] *Queen Mary and Westfield College, London E1 4NS, UK*
[10] *University of California, Los Angeles, CA 90024, USA*
[11] *Universität Mainz, D-55099 Mainz, Germany*
[12] *Universität München, D-85748 München, Germany*
[13] *Carnegie Mellon University, Pittsburgh, PA, USA*
[14] *Centre de Recherches Nucléaires, F-67037 Strasbourg, France*
[15] *Universität Zürich, CH-8001 Zürich, Switzerland*
a) *On leave of absence from the University of Ljubljana, Ljubljana, Slovenia*

Abstract

The rich variety of final states in $\bar{p}p$ annihilation at rest provides a promising environment for meson spectroscopy with particular emphasis on the search for exotic mesons like glue-balls, hybrids, and multi-quark states. Large statistics on pure neutral final states and on final states with charged and neutral particles have been accumulated with the Crystal Barrel Detector at LEAR. In particular, the analysis of 3-pseudoscalar final states $(3\pi^0, 2\pi^0\eta, 2\eta\pi^0, \pi^0\eta\eta')$ has shed light on new scalars with $J^{PC} = 0^{++}$. Two isoscalar 0^{++} resonances, $f_0(1365)$ and $f_0(1520)$, and one isovector 0^{++} resonance, $a_0(1450)$, have been observed and their decay branching ratios into various final states have been determined. The $\pi^0\eta\eta'$ data is well fitted by the hypothesis that it is dominated by $f_0(1520) \to \eta\eta'$. With this assumption, the $f_0(1520)$ shows an interesting decay pattern into $\pi^0\pi^0$, $\eta\eta$, and $\eta\eta'$.

1 Introduction

The Crystal Barrel Spectrometer [1] is a 4π detector for charged and neutral particles (fig. 1). It has a 1.5 Tesla solenoid magnet, inside which are 1380 CsI crystals arranged in a centre pointing (barrel) geometry which are used for photon energy and position measurement (resolution 2.5% at 1 GeV and 20 mrad). Inside this barrel is a cylindrical drift-chamber for measuring charged tracks. At the centre of the detector there is a liquid hydro-

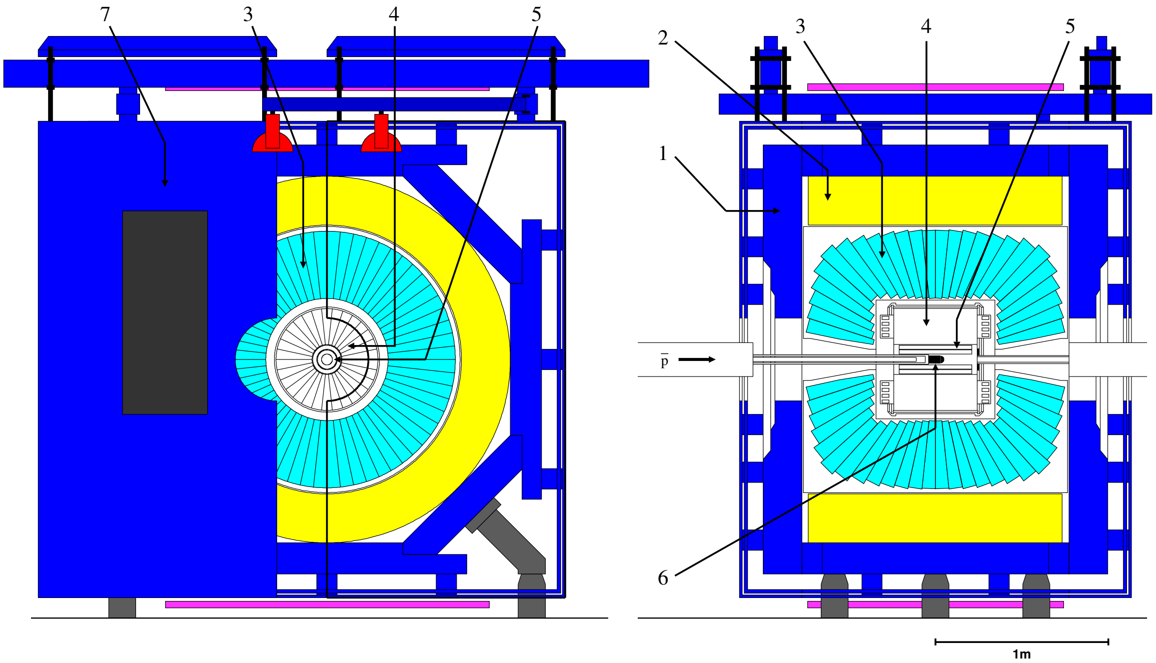

Fig. 1. *The Crystal Barrel Detector. (1) Magnet yoke, (2) magnet coils, (3) CsI calorimeter, (4) drift chamber, (5) proportional wire chambers, (6) target, (7) one half of end plate.*

gen or deuterium target, surrounded by two wire chambers used for triggering on charge multiplicity. Another important feature of the detector is its sophisticated triggering ability, allowing selected final states to be enhanced. It is situated at LEAR and has been used to study low energy antiproton – nucleon annihilations.

One of the main goals of the experiment is to clarify the light meson spectrum, especially by searching for exotic (non $q\bar{q}$) states. The 3 pseudoscalar final states $3\pi^0$, $2\pi^0\eta$, $2\eta\pi^0$, and $\pi^0\eta\eta'$ are particularly well suited to studying the $J^{PC} = 0^{++}$ sector, and the 1^{-+} sector in the case of the $\eta\pi^0\pi^0$ final state.

So far we have published results on part of our data set for $3\pi^0$ and $2\eta\pi^0$. These show the existence of two isoscaler 0^{++} states at masses 1365 and 1520 MeV [2, 3, 4]. An analysis of the $2\pi^0\eta$ data will soon be published [5] showing evidence for a new isovector state at 1450 MeV.

This talk will concentrate on new results derived from the full statistics, and from data taken with a very selective trigger enhancing the $2\eta\pi^0$ and $\pi^0\eta\eta'$ final states.

2 Data Reduction

We have taken 16.8 M $p\bar{p}$ events with an all-neutral trigger, i.e. requiring no hits in the wire chambers. From this data set we selected events with 6 photons above 20 MeV and subjected them to a 4C kinematic fit requiring energy and momentum conservation. 1.4 M events survived, which we subjected to higher constraint fits, combining the photons into all possible final states involving π^0, η, η', and ω mesons. Events were selected for the respective Dalitz plots based on the fit probabilities and the branching ratios for the final states.

To illustrate the quality of the data, consider the hardest case, the $\pi^0\eta\eta'$ final state which has a very small branching ratio into 6γ. We reject any fit with a probability greater than 1% to any other channel or to $\pi^0\pi^0\gamma\gamma$. We then select events with a fit probability greater than 10% to the hypothesis $\pi^0\eta\gamma\gamma$ and plot the $\gamma\gamma$ mass (fig. 2). This shows a clear signal for $\pi^0\eta\eta'$. Fitting the data with a Gaussian plus linear background gives 130 ± 14 signal events. Taking into account the detection efficiency and 2γ meson branching ratios gives

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

We then apply the kinematic constraint that the 2γ make an η' to the events plotted in figure 2: this gives 158 events with a fit probability greater than 10% which we use for the Dalitz plot (fig. 3). We estimate 35 of these 158 events are background from other channels.

The $3\pi^0$, $2\pi^0\eta$, and $2\eta\pi^0$ Dalitz plots contain

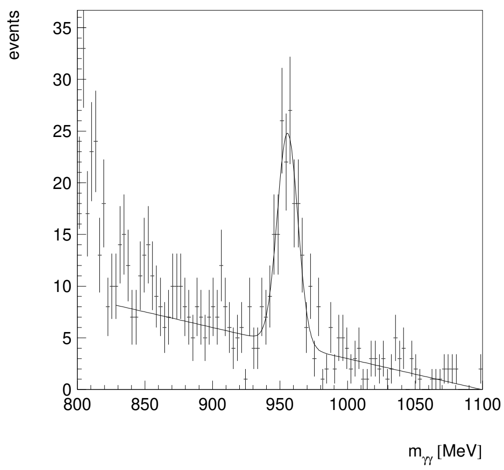

Fig. 2. *The $\gamma\gamma$ invariant mass of the remaining photons after a fit to $\pi^0\eta\gamma\gamma$ (untriggered data set). A gaussian plus linear background fit is superimposed.*

712 k, 187 k, and 31 k events respectively (figs. 4, 5, 6) and are essentially background free. In all cases, the detection efficiency is flat (less than 5% variation).

3 Special Triggered Data

Clearly the $2\eta\pi^0$ and especially the $\pi^0\eta\eta'$ have much lower statistics than the other channels. To enhance their data sets, we have taken data with a very selective trigger. In addition to the usual all-neutral requirements, a hardware module (the "FACE") was used to select events with 5 or 6 clusters of energy deposited in the crystals. Another hardware module selected events with a total energy deposit in the crystals of approximately twice the proton mass. A software trigger analysed the crystal data, calibrating the energy deposits and then used a fast search algorithm to find photons, selecting events with precisely 6. Finally it considered all 15 combinations of pairs of photons into three mesons, and selected events where at least one combination gave invariant masses consistent with either $\pi^0\eta\eta$ or $\pi^0\eta\eta'$.

This data set was analysed as for the all-neutral trigger, giving 160 k $2\eta\pi^0$ events, and 819 $\pi^0\eta\eta'$ events including about 20% background. The special trigger has a very high acceptance of the signals (about 90%). Studies for any variation across the Dalitz plot are underway, but initial conclusions are that if any, it is small. Comparison of special-triggered data with all-neutral data shows good agreement.

4 Dalitz Plot Analysis

We have carried out several analyses of the data. Early work took the Au-Morgan-Pennington [6] amplitudes (AMP) without modification for the $\pi\pi$ S-wave and added further resonances using Breit-Wigner forms. A small subset of the $3\pi^0$ data was fitted with this method and gave a good fit with the introduction of a 2^{++} state, "Ax(1515)", arising largely from atomic P-states. The large P-state contribution in the fit was surprising since most $p\bar{p}$ annihilation in liquid takes place from S-states.

There are two main problems with this approach: firstly, the AMP amplitude applies to $\pi\pi \rightarrow \pi\pi$ scattering – production effects can modify the amplitude in $p\bar{p}$ annihilation; secondly, the addition of two or more Breit Wigners in the same channel can in principle lead to a violation of unitarity – the K-matrix formalism is preferable.

In the first of the new analyses, the first problem is overcome with the N/D method [7] for the $\pi\pi$ S-wave below 1.1 GeV. We add further Breit-Wigners where needed above this mass in the expectation that the second problem is small. The parameters for the denominator D are fixed by fitting $\pi\pi \rightarrow \pi\pi$ data. The numerator is parameterised with 4 complex free parameters to take account of the production effects when fitting to $p\bar{p}$ annihilation data. This analysis gives good fits to the data with all contributions from the $^1S_0$ atomic state. Consistency between the three main channels is ensured by fitting the $3\pi^0$, $2\pi^0\eta$, and $2\eta\pi^0$ Dalitz plots simultaneously.

In the second new analysis, both problems are tackled by using the P-vector approach [8], which is a modification of the K-matrix formalism in which free parameters are introduced (in the P-vector) to account for production effects. In principle one should allow for all possible decay channels of the resonances ($\pi\pi$, $K\bar{K}$, 4π, $\eta\eta\ldots$), but this necessitates too many free parameters, and we restrict ourselves to two channels, $\pi\pi$ and $K\bar{K}$. Good fits are achieved to individual Dalitz plots, either restricting the initial state to $^1S_0$ or allowing P-states as well. In the future we will carry out simultaneous fits to the Dalitz plots with this method.

The two new analyses agree very well, especially in the important conclusions: the necessary introduction of two isoscalar-scalar resonances $f_0(1365)$ and $f_0(1520)$, and an isovector-scalar $a_0(1450)$.

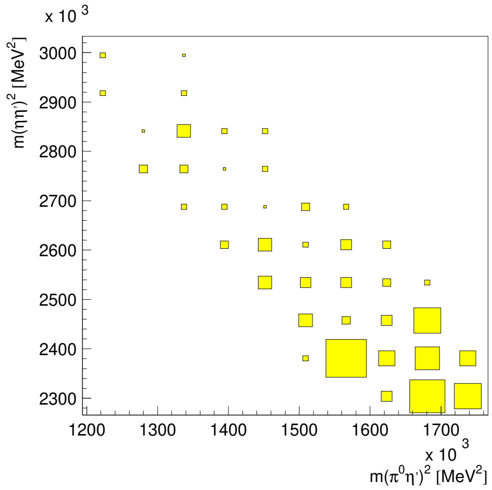

Fig. 3. $\pi^0\eta\eta'$ *Dalitz plot, showing the enhancement at low* $\eta\eta'$ *masses.*

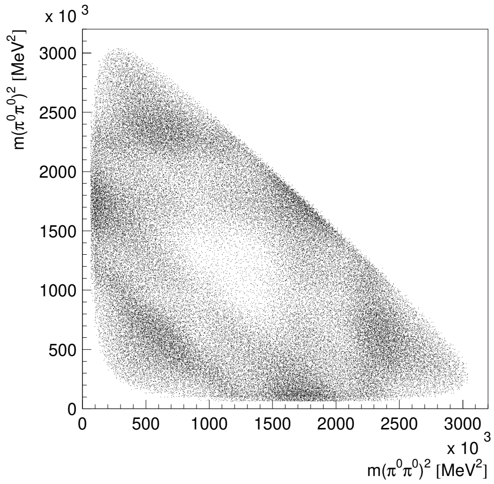

Fig. 4. $3\pi^0$ *Dalitz plot. The band at 2.25 GeV*^{2} *is due to the* $f_0(1520)$*.*

5 Results

5.1 $\pi^0\eta\eta'$ Dalitz Plot

The combined data show a clear enhancement at low $\eta\eta'$ masses. This is what one expects from $p\bar{p} \to f_0\pi, f_0 \to \eta\eta'$, with an f_0 mass below but close to the $\eta\eta'$ threshold. The Dalitz plot is well fitted by a flat background plus a Breit-Wigner 0^{++} state, χ^2/d.o.f. ≈ 1.2. The optimum mass and width in this simple fit are 1545 ± 25 MeV and 100 ± 40 MeV, with 681 events from the Breit Wigner.

5.2 $3\pi^0$ Dalitz Plot

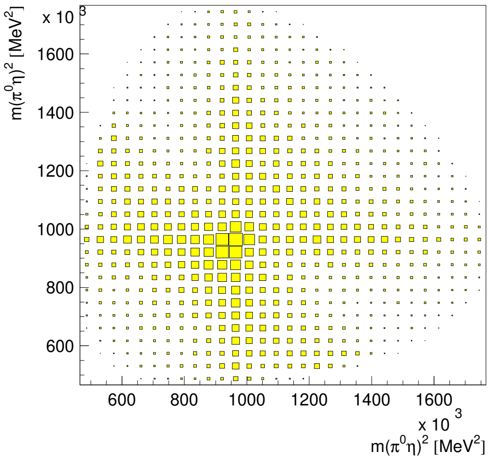

Fig. 5. $2\eta\pi^0$ *Dalitz plot. The lower diagonal band is due to the* $f_0(1520)$*.*

The P-vector analysis is nearing completion. It confirms the earlier results, that the data show contributions from the intermediate states $\pi\pi$ S-wave (containing $f_0(975)$, $f_0(1365)$ and $f_0(1520)$), $f_2(1270)$ and $f_2(1550)$. The mass of the $f_0(1520)$ appears somewhat lower than before, at 1500 MeV. The $f_2(1550)$ contribution is very dependant on the assumptions made for the initial atomic state. It is observed through its interference with the low energy $\pi\pi$ S-wave, and may reflect imperfect parametrisation of this. Alternatively, it may reflect the annihilation dynamics, such as nucleon exchange contributions: so we do not attribute a resonance interpretation to it yet. The $f_0(1365)$ is highly inelastic, unlike the Particle Data Group state at 1400 MeV; indeed, we find its 4π decay is almost 5 times its 2π decay.

5.3 $2\eta\pi^0$ Dalitz Plot

The analysis of the full statistics, including the special triggered data, is continuing. So far, it confirms the previous result that the data show $f_0(1365)$ and $f_0(1520)$ decaying to $\eta\eta$.

5.4 $2\pi^0\eta$ Dalitz plot

Both the new analyses show the existence of an isovector 0^{++} state at 1450 MeV. Without it, the χ^2 of the fits almost double. However, it is obscurred on the Dalitz plot by strong interferences and the strong angular structure of the $a_2(1320)$. The data also show a small but definite $\eta\pi$ P-wave (which has the exotic quantum numbers 1^{-+}). However it appears to be non-resonant. The data exclude the presence of a 1^{-+} resonance with the

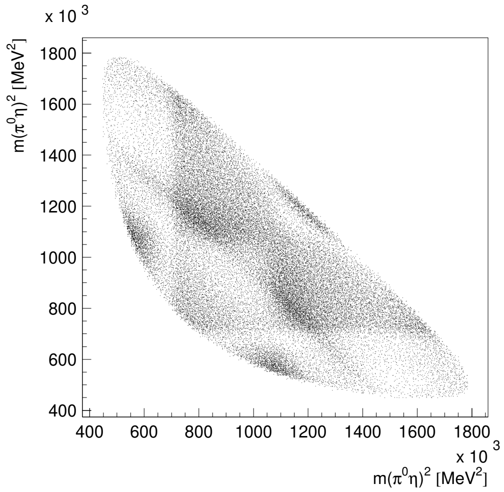

Fig. 6 $2\pi^0\eta$ *Dalitz plot. The* $a_0(1450)$ *is obscured by strong interferences and the angular structure of the* $a_2(1320)$.

parameters reported by GAMS for $\hat{\rho}(1405)$ [9].

6 Conclusions

The $a_0(1450)$ and $f_0(1365)$ have masses close to the well established $K_0^*(1430)$ and fit well into the expected 0^{++} nonet. They could replace the states previously assigned to this nonet, $a_0(980)$ and $f_0(975)$, leaving them free to other interpretations.

We see the $f_0(1520)$ decaying to $\pi^0\pi^0$, $\eta\eta$, and $\eta\eta'$. Under the likely assumption that the $\pi^0\eta\eta'$ final state is dominated by this intermediate state, we obtain the following decay ratios:

$$f_0(1520) \rightarrow$$
$$\begin{array}{cccc} \pi\pi : & \eta\eta : & \eta\eta' : & K\bar{K} \\ 3 : & 0.72 \pm 0.37 : & 1.05 \pm 0.44 : & < 1.4 \end{array}$$

where the upper limit on $K\bar{K}$ is derived from bubble chamber data [10]. We will study the $K\bar{K}\pi^0$ final state in the near future to improve on this limit.

The $K\bar{K}$ decay is smaller (by at least an order of magnitude) than one would expect for an $s\bar{s}$ state, so it seems unlikely to be the ninth member of a nonet. The presence of this extra 0^{++} state leaves the possibility that it is a glueball, strongly mixed with $q\bar{q}$ to explain the decay ratios.

7 References

[1] E. Aker *et al.,* Nucl. Instrum. Methods **A321** 69 (1992)
[2] E. Aker *et al.,* Phys. Lett. **B260** 249 (1991)
[3] C. Amsler *et al.,* Phys. Lett. **B291** 347 (1992)
[4] V. V. Anisovitch *et al.,* Phys. Lett. **B323** 233 (1994)
[5] C. Amsler *et al.,* Accepted for publication in Phys. Lett. (1994)
[6] K.L. Au *et al.,* Phys. Rev. **D35** 1633 (1987)
[7] D.V. Bugg *et al.,* Submittted to Phys. Rev. D (1994)
[8] S.U. Chung *et al.,* Submitted to Z. Phys. C (1994)
[9] M. Boutemeur and M. Poulet, Hadron 89, ed. F. Binon, J.M. Frère, J.P Peigneux (Ed. Frontiérs 1989) p. 119
[10] L. Gray *et al.,* Phys. Rev. **D27** 307 (1983)