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Production and decay of $\eta'(958)$ and $\eta(1440)$ in $\bar{p}p$ annihilation at rest

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Abstract. We report on a study of four reactions in $\bar{p}p$ annihilation at rest, of $\bar{p}p \to 2\pi^+2\pi^-\eta$, $\bar{p}p \to 2\pi^+2\pi^-2\pi^0$, $\bar{p}p \to 2\pi^+2\pi^-\gamma$ and $\bar{p}p \to 4\pi^0\eta$. The η' and the $\eta(1440)$ are seen in their decays into $\pi^+\pi^-\eta$, $\pi^0\pi^0\eta$ and $\pi^+\pi^-\gamma$; no signal is seen in the 4π invariant mass distribution. Branching ratios for η' and $\eta(1440)$ production and decay into the different channels are determined. In particular we derive the ratio $\Gamma_{\eta(1440)\to\pi^+\pi^-\gamma}/\Gamma_{\eta(1440)\to\pi^+\pi^-\eta} = 0.111 \pm 0.064$.

1 Introduction

The E-meson, a resonance at a mass of 1420 MeV with isoscalar and pseudoscalar quantum numbers, was discovered in 1963 in $\bar{p}p$ annihilation at rest [1], but its nature is still controversial. It was seen in the reaction $\bar{p}p \to K\bar{K}3\pi$; the two isobars $a_0(980)\pi$ and K^*K contributed with about equal rates to its decay. In 1980, a resonance with the same quantum numbers and a similar mass and width was observed in radiative J/ψ decays [2]. It was called $\iota(1440)$ and interpreted as glueball. Later, the $\iota(1440)$ was seen to be split into two components [3, 4] which we call $\eta(1405)$ and $\eta(1475)$. The low–mass enhancement was observed to decay into $a_0(980)\pi$ and to $\sigma\eta$ [5] where σ stands for the $(\pi\pi)_S$–wave. A recent high–statistics experiment on π^- proton charge exchange into $\eta\pi\pi$ n at BNL [6] confirmed these findings.

The high–mass state $\eta(1475)$ decays preferentially into K^*K. The Obelix Collaboration took data on $\bar{p}p \to K\bar{K}3\pi$ and reported a pattern of two pseudoscalar states produced in $\bar{p}p$ annihilation at rest [7] with masses compatible with the findings from J/ψ decay [3].

The existence of two resonances in a narrow mass range – or even three when the $\eta(1295)$ is also considered – poses severe problems to any quark model, and an exotic interpretation of at least one of these states seems required.

The two proposed resonances $\eta(1405)$ and $\eta(1475)$ may contribute in a different way to radiative J/ψ decays and to $\bar{p}p$ annihilation at rest. For the unresolved structure produced in radiative J/ψ decays we use the name $\iota(1440)$; for the unresolved state produced in $\bar{p}p$ annihilation at rest

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we use its old name E–meson. A short review of the status can be found in [8].

In this paper we report studies on the E–meson as produced in the reactions

$$\bar{\mathrm{p}}\mathrm{p} \to 2\pi^+2\pi^-\eta \quad (1)$$

$$\bar{\mathrm{p}}\mathrm{p} \to 2\pi^+2\pi^-\gamma \quad (2)$$

$$\bar{\mathrm{p}}\mathrm{p} \to 4\pi^0\eta \quad (3)$$

$$\bar{\mathrm{p}}\mathrm{p} \to 2\pi^+2\pi^-2\pi^0 \quad (4)$$

with antiprotons stopping in liquid H_2. The π^0 and η are detected in their 2γ decay modes.

From the comparison of reactions (1) and (4) we derive an upper limit for the 4π decay mode of the $\eta(1405)$. In reactions (1-3) we observe the η' and the $\eta(1405)$ and determine their respective branching ratios. The $f_1(1420)$ is not produced in $\bar{\mathrm{p}}\mathrm{p}$ annihilation at rest in liquid H_2 [9], but rather only in gaseous H_2 [10]. Hence any possible signal in our data in the $\rho\gamma$ mass distribution at ∼1400 MeV can be associated with the $\eta(1405)$. A partial wave analysis of reaction (1) was presented in [12].

2 Experiment and data reduction

2.1 The crystal barrel experiment at LEAR

The data on reactions (1-4) were recorded with the Crystal Barrel detector at the Low Energy Antiproton Ring LEAR at CERN. The detector was described in detail elsewhere [11]; here we give only a brief overview. A 200 MeV/c $\bar{\mathrm{p}}$ beam stopped in a liquid hydrogen target at the center of the detector. The H_2 target was surrounded by a silicon vertex detector (SVTX); its main purpose was the possibility to trigger on K^0_s decays but it also provided a precise tracking point close to the target yielding an improved momentum resolution [13]. The main tracking device for charged particles was a cylindrical drift–chamber (JDC) with 23 layers. Together with the SVTX, a momentum resolution of $\delta p/p = 4.5\%$ at 1 GeV/c was obtained.

The JDC was surrounded by a barrel consisting of 1380 CsI(Tl) crystals, pointing towards the center of the target. The CsI calorimeter covered the polar angles between 12° and 168° with full coverage in azimuth. The useful acceptance for shower detection was $0.95 \times 4\pi$ sr. Typical photon energy resolutions are $\sigma_E/E = 2.5\%$ at 1 GeV, and $\sigma_{\Theta,\Phi} = 1.2°$ in both polar and azimuthal angles. The full assembly was placed inside of a conventional magnet providing a field of 1.5 T.

The data were recorded under three different trigger conditions. All three triggers required an antiproton stopping in the target. No further conditions were imposed for the first *minimum bias* trigger used for normalization; $1.842 \cdot 10^6$ events were recorded. The second *four–prong* trigger asked for exactly 4 hits in the last two layers of the JDC thus selecting events with 4 long tracks in the JDC giving the best momentum resolution. The number of events taken under these conditions was $7.3 \cdot 10^6$. Finally, $15 \cdot 10^6$ events were taken with a *zero–prong* trigger vetoing events with hits in one of the inner layers of the JDC.

2.2 Data reduction

The *four–prong* triggered data were analyzed finding ∼ 4.9 million events which had exactly 4 tracks with total charge zero and a vertex in the H_2 target. The events were classified according to the number of contiguous energy deposits in the crystal barrel which we call Particle Energy Deposits (PEDs). PEDs were accepted if they had a minimum total energy of 14 MeV and if the maximum energy deposit was not in one of the crystals surrounding the beam pipe (since in these events a significant fraction of the PED energy could be lost along the beam pipe).

Tracks of charged particles were reconstructed in the JDC; the track was then projected onto the crystal matrix. The closest shower was associated with the track. These showers were removed from the list of PEDs; only unmatched PEDs were considered as photons. We retained events with one to four photons. Events can be lost when photons or charged particles remain undetected (due to the limited acceptance); these losses are well described by Monte Carlo simulations. Events may however also be lost when spurious particles are created by splitting of tracks into two parts or by shower fluctuations. The former effect was controlled by visual inspection of real data and of Monte Carlo events; it poses no quantitative problem. The latter effect was corrected for by Monte Carlo simulations.

Shower fluctuations may cause unphysical energy deposits which we call split–offs. Split–offs from electromagnetic showers identify themselves mostly by their small energy deposit and closeness to their parent PEDs and can be rejected efficiently. Furthermore, they are well reproduced by our Monte Carlo simulation. Indeed, a large number of branching ratios for reactions like $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\eta$ with η decaying into 2 or – through $3\pi^0$ – into 6γ's have been determined [14], with an excellent consistency. Hadronic split–offs were also observed both in real and in Monte Carlo data. The simulation of the passage of low–momentum particles through our detector was based on the Geisha program (within the GEANT package). If hadronic split–offs were close to the track they were recognized as such and suppressed. There was however a chance that a split–off (in particular a hadronic split–off) escaped unrecognized. These events were then believed to have 3 detected γ's. We searched for $\pi^+\pi^-\pi^+\pi^-\eta$ events in the 3γ–event–sample by removing one of the three γ's and fitting kinematically the four tracks plus the remaining two γ's to the $\pi^+\pi^-\pi^+\pi^-\eta$ hypothesis, imposing energy and momentum conservation and the η mass (five constraints). We recovered 25% additional events both in real data and in Monte Carlo data. Hence also hadronic split–offs are correctly described by our Monte Carlo simulation. We did not use these additional events for further analysis since they suffer from a larger background.

We first discuss reaction (1). The data with exactly 2γ's were subjected to kinematic fits imposing energy and momentum conservation (four constraints = 4C). After a

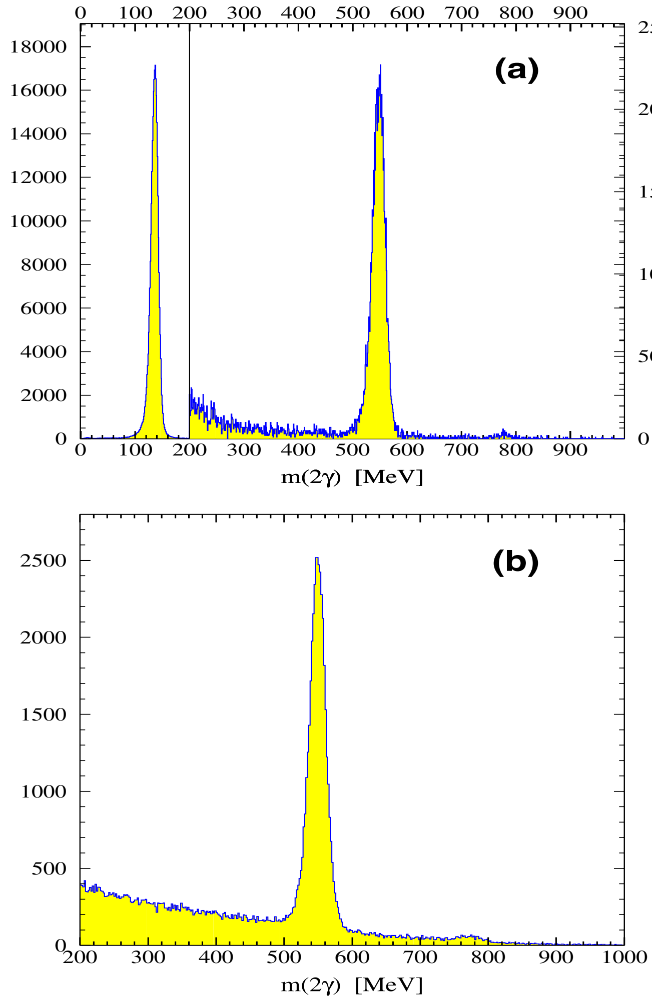

Fig. 1a,b. 2γ invariant mass distribution for the reaction $\bar{\mathrm{p}}\mathrm{p} \to 2\pi^+2\pi^-2\gamma$ after a fit imposing energy and momentum conservation (4C fit) **a** and for the reaction $\bar{\mathrm{p}}\mathrm{p} \to 4\pi^0 2\gamma$ (8C fit) **b**

probability cut of 10%, we arrived at a 2γ invariant mass distribution with two peaks at the π^0 and η masses which is shown in Fig. 1a. Note the different scale for the π^0 and η peak height. The π^0 and the η mesons are observed above a very small residual background.

The data were then fitted to the $2\pi^+2\pi^-\pi^0$ or $2\pi^+2\pi^-\eta$ hypothesis, respectively, imposing 5 constraints (energy and momentum conservation and the π^0 or η mass). After a 10% confidence level cut, we retained 267 741 $2\pi^+2\pi^-\pi^0$ events and 6026 events for reaction (1).

For *minimum bias* we used the same series of cuts and found 11 968 $2\pi^+2\pi^-\pi^0$ events. From this ratio we determine the effective number of $\bar{\mathrm{p}}\mathrm{p}$ annihilations for the data taken with the *four–prong* trigger: $(39.9 \pm 1.4) \cdot 10^6$. This number includes a correction of 0.97 ± 0.02 for antiprotons giving a trigger but which do not stop in the target.

The acceptance of the detector was determined from Monte Carlo simulations. We found an acceptance of (4.31 $\pm$0.68)% for reaction $\bar{\mathrm{p}}\mathrm{p}\to2\pi^+2\pi^-\pi^0$ and thus a branching ratio of $BR(\bar{p}p \to 2\pi^+2\pi^-\pi^0) = (15.6 \pm 2.8)\%$.

This branching ratio had been determined (more precisely) in bubble chamber experiments to be $(17.3 \pm 0.6)\%$ [15] and $(18.7 \pm 0.9)\%$ [16], respectively. Our value and these two values are compatible. We normalize our branching ratios to their weighted mean value which is $(17.7 \pm 0.5)\%$.

For reaction (1) we found a reconstruction efficiency of $(1.22 \pm 0.12)\%$ when the $\eta \to 2\gamma$ decay fraction [18] was included, and a branching ratio of

$$BR(\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\eta) = (1.24 \pm 0.12)\%. \quad (5)$$

This ratio includes contributions from $\pi^+\pi^-\eta'$ with $\eta' \to \pi^+\pi^-\eta$.

We now turn to a discussion of reaction (2). We identified the reaction in a 4–constraint fit. Events which were compatible with the $2\pi^+2\pi^-$ hypothesis in a 4 constraint fit were removed. In this analysis we are interested in η' and $\eta(1405)$ decays into $\pi^+\pi^-\gamma$, mostly into $\rho\gamma$. Isospin conservation forbids η' and $\eta(1405)$ decays into $\pi^+\pi^-\pi^0$. Peaks in the $\pi^+\pi^-\gamma$ invariant mass must therefore stem from η' and $\eta(1405)$ decays into $\pi^+\pi^-\gamma$.

The confidence–level distribution after a 4–constraint (4C) fit gave a rising number of events with low confidence reflecting a large background contamination from $2\pi^+2\pi^-\pi^0$ with one lost photon. To avoid uncontrolled losses we retained events with a c.l. of $> 1\%$.

Reaction (4) is studied by selecting events with four photons and applying a kinematic fit to the $2\pi^+2\pi^-2\pi^0$ and $2\pi^+2\pi^-\pi^0\eta$ hypotheses. After a cut in the confidence level distribution at 10% of the $2\pi^+2\pi^-2\pi^0$ and an anti–cut at 0.1% of the $2\pi^+2\pi^-\pi^0\eta$ hypothesis we found 105,621 events which we used to search for $\rho^+\rho^-$ decays of the η (1405).

The data collected with the *zero–prong* trigger were scanned for events with charged–tracks (from Dalitz pairs $\gamma \to e^+e^-$ conversion, backscattered particles, etc.) and split into subsamples with a defined number of PEDs in the barrel, $1.5 \cdot 10^6$ events were found in the 10γ event class. They underwent a series of kinematic fits. A 4–constraint (4C) fit imposed energy and momentum conservation. After a cut at 10% in the confidence level, 539k events survived which are mostly due to annihilation into $5\pi^0$ and to residual background. We next applied a 9C kinematic fit imposing energy and momentum conservation and $5\pi^0$ masses; we found 362k $5\pi^0$ events with a confidence level exceeding 10%. Events which do not pass this fit were subjected to an 8C fit in which only four π^0 masses were required. The 2γ invariant mass distribution of the two photons which do not combine to a π^0 are plotted in Fig. 1b. Clearly, the reaction $\bar{\mathrm{p}}\mathrm{p}\to4\pi^0\eta$ is observed. Finally, we performed a 9C kinematic fit imposing four π^0 masses and one η mass and retain events with a confidence level exceeding 10%. The detection efficiency for the $4\pi^0\eta$ channel (including the $\eta\to2\gamma$ fraction) is $(3.76 \pm 0.38)\%$.

The Crystal Barrel collaboration has reported a consistent set of all–neutral annihilations [17], including the branching ratio

$$BR(\bar{p}p \to 4\pi^0\eta) = (2.37 \pm 0.12) \cdot 10^{-3}. \quad (6)$$

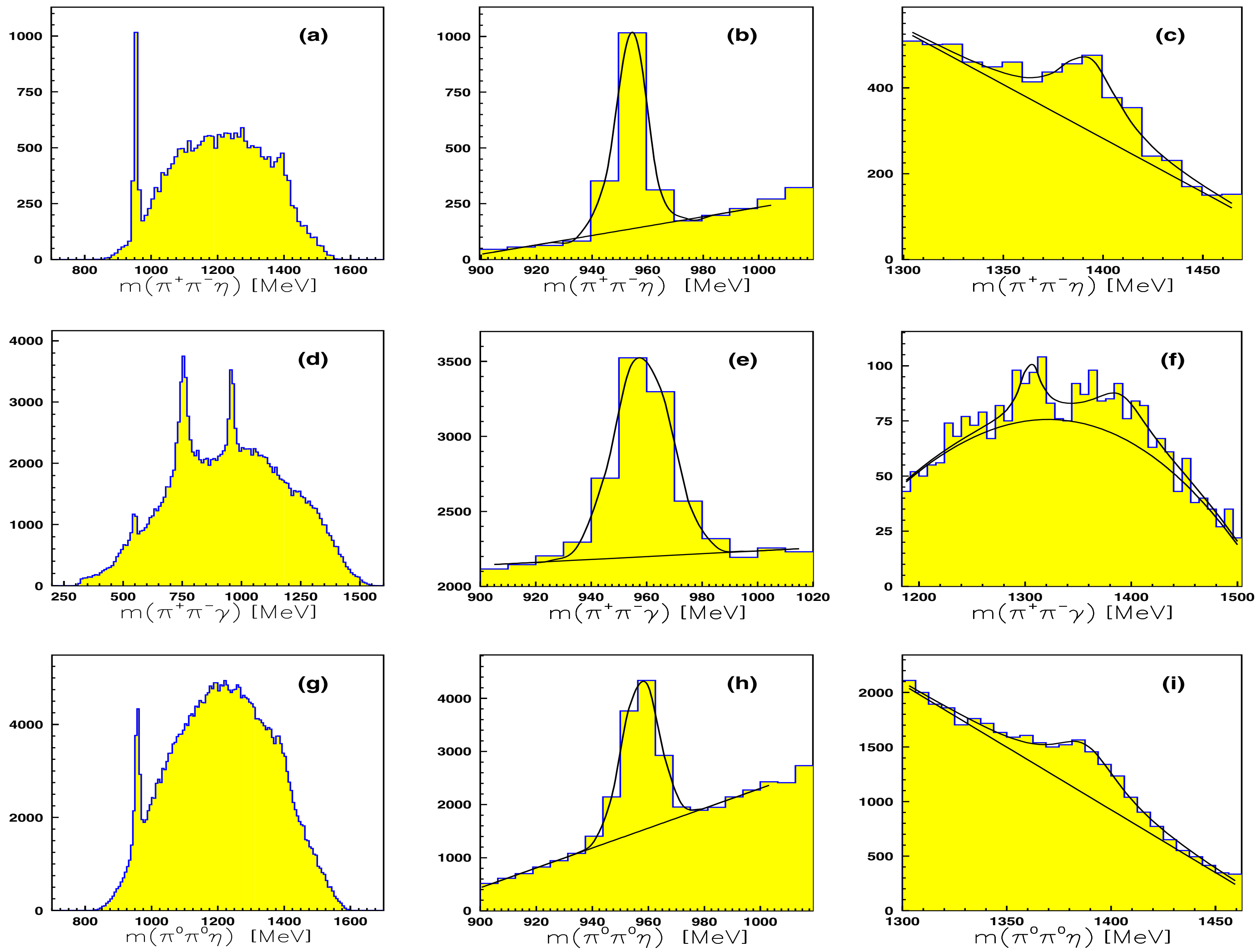

Fig. 2. **a** $\pi^+\pi^-\eta$ invariant mass distribution; **b** expanded view showing the η'; **c** expanded view around 1400 MeV. **d** $\pi^+\pi^-\gamma$ invariant mass distribution; **e** expanded view showing the η'; **f** expanded view around 1400 MeV after further cuts (see text). **g** $\pi^0\pi^0\eta$ invariant mass distribution; **h** expanded view showing the η'; (i): expanded view around 1400 MeV after removal of the η'

3 Branching ratios

3.1 The ratio η' to $\pi^+\pi^-\gamma$ and $\pi^+\pi^-\eta$

Figure 2a shows the $\pi^+\pi^-\eta$ invariant mass distribution for reaction (1). There is evidence for two structures, at the nominal η' mass and at 1405 MeV. A fit to the η' region (Fig. 2b) gives 1272 ± 43 events due to the η'. Using the Monte Carlo efficiency of $(1.16\pm0.11)\%$, we deduce a branching ratio of

$$BR(\bar{p}p \to \pi^+\pi^-\eta'; \eta' \to \pi^+\pi^-\eta) = (2.74\pm0.30)\cdot10^{-3}. \quad (7)$$

This and further results are collected in Table 1 and Table 2. The value (7) compares very favorably with our previous result of $(7.5\pm2.0)\cdot10^{-3}$ [5] when the $\eta'\to\pi^+\pi^-\eta$ decay fraction of $(43.8\pm1.5)\%$ is taken into account but disagrees with the value found in [20].

The contribution of the η' to reaction (1) is given in (7). We may subtract this part from (5) and we obtain

$$BR(\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\eta) = (0.97\pm0.12)\,\%\ \text{(excluding } \eta'). \quad (8)$$

In Fig. 2d we show the $\pi^+\pi^-\gamma$ mass distribution for events from reaction (2). Three signals are observed. The peak at the highest energy is due to η' production and decay into $\pi^+\pi^-\gamma$. Note that the peak cannot have contributions from $\pi^+\pi^-\pi^0$. The central signal stems from ω production and its decay to $\pi^+\pi^-\pi^0$; $\pi^0\to\gamma\gamma$ with one low–energy photon missing. The low–mass peak originates from η decays into $\pi^+\pi^-\gamma$ and into $\pi^+\pi^-\pi^0$ (with one missing photon).

The extended view in Fig. 2e shows a fit to the η' region giving 3484 ± 700 η' events. The Monte Carlo detection efficiency for this channel is $(6.31\pm1.27)\%$. These numbers lead to a branching ratio of

Table 1. Event numbers, detection efficiencies and branching ratios for η' production. The efficiencies contain the $\eta\to 2\gamma$ decay fraction

Reaction	$\pi^+\pi^-\eta'$; $\eta'\to\pi^+\pi^-\eta$	$\pi^+\pi^-\eta'$; $\eta'\to\pi^+\pi^-\gamma$	$\pi^0\pi^0\eta'$; $\eta'\to\pi^0\pi^0\eta$
N	1272 ± 43	3484 ± 700	9426 ± 840
ϵ	$(1.16\pm 0.11)\%$	$(6.31\pm 1.27)\%$	$(3.82\pm 0.39)\%$
BR $[10^{-3}]$	2.74 ± 0.30	1.38 ± 0.40	0.31 ± 0.04

Table 2. Event numbers, detection efficiencies and branching ratios for $\eta(1405)$ production. The efficiencies contain the $\eta\to 2\gamma$ decay fraction

Reaction	$\pi^+\pi^-\eta(1405)$; $\eta(1405)\to\pi^+\pi^-\eta$	$\pi^+\pi^-\eta(1405)$; $\eta(1405)\to\pi^+\pi^-\gamma$	$\pi^0\pi^0\eta(1405)$; $\eta(1405)\to\pi^0\pi^0\eta$
N	900 ± 375	235 ± 91	6609 ± 1990
ϵ	$(1.19\pm 0.11)\%$	$(2.81\pm 0.28)\%$	$(3.49\pm 0.48)\%$
BR $[10^{-3}]$	1.89 ± 0.81	0.21 ± 0.08	0.23 ± 0.08

$$BR(\bar{p}p\to\pi^+\pi^-\eta';\eta'\to\pi^+\pi^-\gamma) = (1.38\pm 0.40)\cdot 10^{-3}. \quad (9)$$

From the ratio of the two frequencies (9), (7) we find

$$\frac{\Gamma_{\eta'\to\pi^+\pi^-\gamma}}{\Gamma_{\eta'\to\pi^+\pi^-\eta}} = 0.50\pm 0.16 \quad (10)$$

in reasonable agreement with the PDG value of 0.63 ± 0.06.

3.2 The ratio $\eta(1405)$ to $\pi^+\pi^-\gamma$ and $\pi^+\pi^-\eta$

The enhancement at 1405 MeV in Fig. 2a is assigned to the $\eta(1405)$. In an earlier paper we have shown that the structure has indeed pseudoscalar quantum numbers [5]. Figure 2c shows an extended view of the $\pi^+\pi^-\eta$ signal in the mass region around 1400 MeV. A fit to the data with a Voigt function (a convolution of Breit–Wigner and Gauss functions) and a polynomial background gives a mass $M = 1392\pm 14$ MeV and a width $\Gamma = 55\pm 11$ MeV; 900 ± 375 events are assigned to the $\eta(1405)$. The error includes the range of values when the background function is varied. With a Monte Carlo detection efficiency of $(1.19\pm 0.11)\%$ we arrive at

$$BR(\bar{p}p\to\pi^+\pi^-\eta(1405);\eta(1405)\to\pi^+\pi^-\eta) = (1.89\pm 0.81)\cdot 10^{-3} \quad (11)$$

in agreement with [5].

The background in the $\eta(1405)$ region in Fig. 2d is rather large so that no signal is visible. Therefore we introduce further cuts: we require that the $\pi^+\pi^-$ invariant mass exceeds 600 MeV, the γ–energy should exceed 450 MeV and the confidence level for the $\pi^+\pi^-\pi^+\pi^-\gamma$ hypothesis should be $> 10\%$. These cuts reduce only slightly the number of events due to $\eta(1405)\to\rho\gamma$ decays. Figure 2f shows the invariant mass distribution after these cuts. Two peaks are now visible. Their statistical significance is 3.3 and 2.7 standard deviations, respectively. The low–mass peak is assigned to the $X(1285)$ which we assume to be the $f_1(1285)$ (even though we cannot exclude that it is due to the $\eta(1295)$). It is fitted with $f_1(1285)$ PDG mass and width; 204 ± 68 events are assigned to the peak. With a Monte Carlo detection efficiency for $X(1285)$ of $(3.24\pm 0.33)\%$ we find a branching ratio for the reaction chain $\bar{\text{p}}\text{p}\to\pi^+\pi^- X(1285), X\to\rho\gamma$ of $(0.16\pm 0.06)\cdot 10^{-3}$. With $\eta(1295)$ parameters for the $X(1285)$, the branching ratio changes insignificantly only.

The $\eta(1405)$ is fitted with a mass $M = 1390\pm 12$ MeV and a width $\Gamma = 64\pm 18$ MeV. The number of $\eta(1405)$ is determined to 235 ± 91. With a Monte Carlo detection efficiency of $(2.81\pm 0.28)\%$, we arrive at

$$BR(\bar{p}p\to\pi^+\pi^-\eta(1405);\eta(1405)\to\pi^+\pi^-\gamma) = (0.21\pm 0.08)\cdot 10^{-3}. \quad (12)$$

The error includes the uncertainty in the background subtraction when the mass range and the order of the polynomial background function is changed.

From (11,12) we determine

$$\frac{\Gamma_{\eta(1405)\to\pi^+\pi^-\gamma}}{\Gamma_{\eta(1405)\to\pi^+\pi^-\eta}} = 0.111\pm 0.064. \quad (13)$$

A comparison with previous results is made in the conclusions.

3.3 Spin–singlet and triplet contributions to $\pi\pi\eta'$

Figure 2g,h show the $\pi^0\pi^0\eta$ invariant mass distribution from reaction (4) with clear peaks due to the η'. Their number is determined to be 9426 ± 840. With the Monte Carlo detection efficiency of $(3.82\pm 0.39)\%$ we find

$$BR(\bar{p}p\to\pi^0\pi^0\eta';\eta'\to\pi^0\pi^0\eta) = (0.31\pm 0.04)\cdot 10^{-3}. \quad (14)$$

Correcting for unseen η' decay modes [18], we find

$$BR(\bar{p}p\to\pi^0\pi^0\eta') = (1.50\pm 0.31)\cdot 10^{-3}, \quad (15)$$

$$BR(\bar{p}p\to\pi^+\pi^-\eta') = (6.26\pm 0.72)\cdot 10^{-3}. \quad (16)$$

Reaction (16) contributes to $\bar{\text{p}}\text{p}$ annihilation from states with positive and negative C–parity (these are the $^1\text{S}_0$ and

$^3S_1$ states of the $\bar{p}p$ system, respectively, when S–wave dominance is assumed). Reaction (15) is restricted to initial states with positive C–parity. Taking the Clebsch–Gordan coefficients for $\pi^+\pi^-$ and $\pi^0\pi^0$ production into account one finds that negative C–parity states give a contribution of $(3.26 \pm 0.95) \cdot 10^{-3}$. The fraction of initial $\bar{p}p$ states with negative C–parity contributing to (16) is 0.52 ± 0.06; this fraction is mainly due to $\rho\eta'$ production. In two partial wave analyses [20, 21] the fraction of $\rho\eta'$ in $\pi^+\pi^-\eta'$ was determined to 0.51 ± 0.10 and 0.54 ± 0.12, respectively. Our result is in good agreement with those findings.

3.4 Spin–singlet and triplet contributions to $\pi\pi\eta(1405)$

After a cut on the η' in the $4\pi^0\eta$ data to remove some combinatorial background we obtain the spectrum shown in Fig. 2i with clear evidence for the $\eta(1405)$. The fit finds 6609 ± 1990 $\eta(1405)$ events for which we derive a branching ratio of

$$BR(\bar{p}p \to \pi^0\pi^0\eta(1405); \eta(1405) \to \pi^0\pi^0\eta) = (0.23 \pm 0.08) \cdot 10^{-3}. \quad (17)$$

From this data we find a mass $M = 1394 \pm 8$ MeV and a width $\Gamma = 55 \pm 12$ MeV. Including $\eta(1405)$ decays into $\pi^+\pi^-\eta$ we can compare the $\eta(1405)$ production rates (with $\eta(1405) \to \pi\pi\eta$)

$$BR(\bar{p}p \to \pi^0\pi^0\eta(1405)) = (0.71 \pm 0.24) \cdot 10^{-3}, \quad (18)$$

$$BR(\bar{p}p \to \pi^+\pi^-\eta(1405)) = (2.84 \pm 1.22) \cdot 10^{-3}. \quad (19)$$

The $^1S_0$ initial state contributes to (18) and to (19), the $^3S_1$ to (19) only. The $^1S_0$ contribution to (19) is twice the value of (18). Hence we can determine the contribution from the $^3S_1$ state:

$$BR(\bar{p}p \to \rho\eta(1405)) = (1.42 \pm 1.31) \cdot 10^{-3}. \quad (20)$$

The reaction $\bar{p}p \to \rho\eta(1405)$ is kinematically not allowed for the central ρ mass; the ρ stands for $\pi^+\pi^-$ pairs with isospin $I = 1$. Production of $\pi^0\pi^0\eta(1405)$ from $\bar{p}p$ atomic S–states proceeds via the $^1S_0$ state, production of $\rho\eta(1405)$ via the $^3S_1$ state. The fraction of the $^1S_0$ state and $^3S_1$ state to the reaction $\bar{p}p \to \pi^+\pi^-\eta(1405)$ cannot be determined from these data.

3.5 The $\eta(1405)$ into $\pi\pi\eta$ and $K\bar{K}\pi$

Baillon et al. [1] performed a partial wave analysis of the reaction chain $\bar{p}p \to \pi^+\pi^-E(1420)$ with $E(1420) \to K\bar{K}\pi$. Pseudoscalar quantum numbers were found and contributions from the $^3S_1$ and $^1S_0$ state were determined to be (2.0 ± 0.2) and $(0.6 \pm 0.06) \cdot 10^{-3}$, respectively.

We now derive the ratio of $\eta(1405)$ decays into $\pi\pi\eta$ and $K\bar{K}\pi$ and find

$$\frac{\Gamma_{\eta(1405)\to\pi\pi\eta}}{\Gamma_{\eta(1405)\to K\bar{K}\pi}} = 1.09 \pm 0.48. \quad (21)$$

The partial wave analysis in [1] was performed assuming that the reaction is dominated by the reaction $\bar{p}p \to \pi^+\pi^-E(1420)$. Later unpublished work allowed for a 20-30% contribution from direct $K^*\bar{K}\pi\pi$ production [22]. This result would change the ratio (21) to 0.90 ± 0.40. A comparison with results from radiative J/ψ decays is made in the conclusions.

3.6 Search for $\eta(1405)$ decays into $\rho^+\rho^-$

The $\eta(1405)$ may decay into $\rho\rho$ via two reaction chains, $\bar{p}p \to 2\pi^0\eta(1405)$; $\eta(1405) \to \rho^0\rho^0$ or $\bar{p}p \to \pi^+\pi^-\eta(1405)$; $\eta(1405) \to \rho^+\rho^-$. The latter reaction is four times more sensitive and we use it to demonstrate the absence of this decay mode. The data on $\bar{p}p \to 2\pi^+2\pi^-2\pi^0$ contain a large fraction of ω mesons; a cut to remove the ω from the data results in a large loss of data and sensitivity. Figure 3 shows the $\pi^+\pi^-2\pi^0$ invariant mass spectrum for this reaction without any cuts.

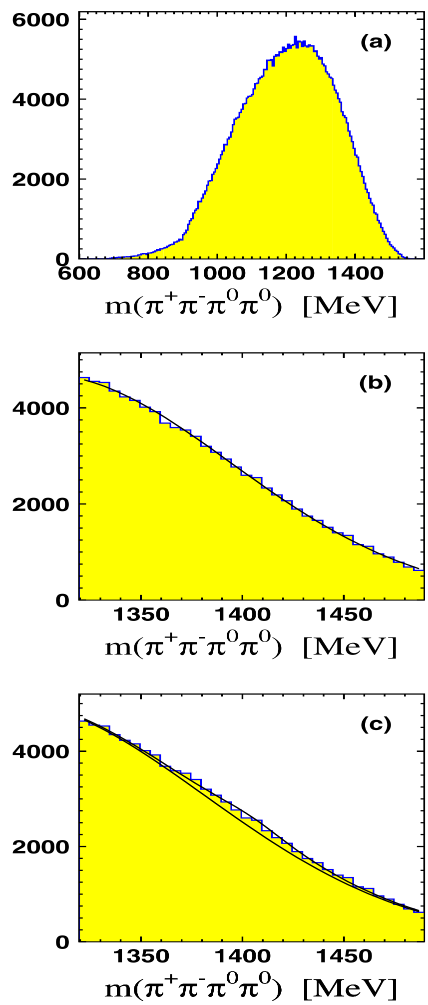

Fig. 3. $\pi^+\pi^-2\pi^0$ invariant mass distribution for the reaction $\bar{p}p \to 2\pi^+2\pi^-2\pi^0$; full distribution **a** and expanded 1400 MeV region **b,c**. Fig. **b** shows the best fit with no $\eta(1405)$, Fig. **c** a fit yielding 4200 events from $\eta(1405)$ **c**. The latter fit leads to an increase in χ^2 of 9 units

Table 3. The $\eta(1405)$ partial decay width $\Gamma_{\pi^+\pi^-\gamma}$

Reference	[24]	[30]	[31]	this work
$\Gamma_{\pi^+\pi^-\gamma}[MeV]$	4.77 ± 2.29	3.45 ± 1.58	7.64 ± 4.59	2.51 ± 1.26

The data do not show a contribution from the $\eta(1405)$ and we derive a 3σ upper limit of 4200 events. Including the reconstruction efficiency for this channel of $(2.07 \pm 0.46)\%$ and the Clebsch–Gordan coefficient for decays into $\rho^+\rho^-$ of 2/3, we arrive at an upper limit

$$BR(\bar{p}p \to \pi^+\pi^-\eta(1405); \eta(1405) \to \rho\rho) < 8 \cdot 10^{-3}. \quad (22)$$

We add the two branching ratios for $\bar{\mathrm{p}}\mathrm{p} \to \pi^+\pi^-\eta(1405)$ given in (19) and by Baillon et al. [1] and find a total production rate of

$$BR(\bar{p}p \to \pi^+\pi^-\eta(1405)) = (5.44 \pm 1.25) \cdot 10^{-3} \quad (23)$$

per annihilation. Here we assume that $\pi\pi\eta$, $\mathrm{K}\overline{\mathrm{K}}\pi$ and $\rho\rho$ are the dominant decay modes of the $\eta(1405)$. We find a 3σ upper limit for the fractional $\eta(1405) \to \rho\rho$ decay of 0.58.

4 Conclusions

We have studied three reactions in which the η' and the $\eta(1405)$ contribute via their $\pi^+\pi^-\eta$, $\pi^0\pi^0\eta$ and their $\pi^+\pi^-\gamma$ decays. The branching ratios are reasonably consistent with former experiments giving credit to the newly derived results. In particular we derive the ratio

$$\frac{\Gamma_{\eta(1405)\to\pi\pi\eta}}{\Gamma_{\eta(1405)\to\mathrm{K}\bar{\mathrm{K}}\pi}} = 1.09 \pm 0.48$$

using the E$\to$ $\mathrm{K}\overline{\mathrm{K}}\pi$ result from [1]. The Particle Data Group classifies both decay modes as *seen*. From [23] and [3, 24] we determine the ratio from radiative J/ψ data to 0.56 ± 0.16. The BES collaboration quotes 0.36 without giving an error [25]. We note that radiative J/ψ decays into $\mathrm{K}\overline{\mathrm{K}}\pi$ contain contributions from the $a_0(980)\pi$ and $\mathrm{K}^*\mathrm{K}$ isobars which seem to resonate at different masses. If the two components of the $\iota(1440)$ corresponded to two different states with possibly different couplings to J/ψ and $\bar{\mathrm{p}}\mathrm{p}$, then the comparison of J/ψ and $\bar{\mathrm{p}}\mathrm{p}$ data would be meaningless. Nevertheless, we list those ratios from radiative J/ψ decays for comparison.

Conflicting data exist for the $\rho\rho$ decay mode of the $\iota(1440)$. DM2 analyzed $\mathrm{J}/\psi \to \gamma 2\pi^+ 2\pi^-$ data and reported a pseudoscalar $\rho\rho$ resonance at 1489 MeV [29]. This signal could be due to the $\eta(1475)$. It could, however, also be due to a state which is now known as $f_0(1500)$, in agreement with the partial wave reanalysis of MARK III data [26] and with recent BES data [27]. Allowing for $\rho^+\rho^-$ decays in addition to the observed $\rho^0\rho^0$ decay, the $\iota(1440) \to \rho\rho$ decay fraction into $\rho\rho$ is $\sim$75%.

In the recent BES data, a pseudoscalar resonance at 1440 MeV is seen but with a width of 225 MeV [27] or possibly a much broader width [28]. The data seem not to support $\iota(1440)$ decays into $\rho\rho$. The observation or non–observation of the $\rho\rho$ decay mode with the strength reported in [26] is an important issue: it changes all partial widths of the $\eta(1405)$ or $\eta(1475)$ by a large amount.

We do not find a 4π decay of the $\eta(1405)$ and determine a 3σ upper limit of

$$\frac{\Gamma_{\eta(1405)\to 4\pi}}{\Gamma_{\eta(1405)\to(all)}} < 0.58. \quad (24)$$

Of particular importance are radiative decays of the $\eta(1405)$. In this paper we have determined the ratio

$$\frac{\Gamma_{\eta(1405)\to\pi^+\pi^-\gamma}}{\Gamma_{\eta(1405)\to\pi^+\pi^-\eta}} = 0.111 \pm 0.064.$$

From this ratio we derive the $\Gamma_{\eta(1405)\to\pi^+\pi^-\gamma}$ partial width.

Assuming the $\eta(1405)$ decay modes into $\mathrm{K}\overline{\mathrm{K}}\pi$ and $\pi\pi\eta$ to be the most significant ones, we find a $\eta(1405) \to \rho\gamma$ partial decay width as given in Table 3.

The search for radiative decays of the $\iota(1440)$ has played a major role at the time when the $\iota(1440)$ was interpreted as a glueball. Naively, one may expect radiative decays to couple to the charge of constituent particles and hence radiative decay rates should vanish or at least be small for a meson with a large fraction of constituent glue. Hence the observation of $\eta(1405) \to \pi^+\pi^-\gamma$ decays constrains the nature of the $\eta(1405)$. In searches for radiative decays of the $\iota(1440)$, clear signals were observed in J/ψ decays into $\gamma(\rho\gamma)$ in the $\rho\gamma$ invariant mass distribution at 1401 MeV [24] and 1440 MeV [30], respectively. However the data did not allow spin–parity analyses and hence it was unclear whether the signal has to be assigned to $\eta(1405)$ production or to the $f_1(1420)$ which was also observed in radiative J/ψ decays. Recently, the reaction $\mathrm{J}/\psi \to \gamma(\rho\gamma)$ was studied at BES with similar accuracy [31] but the ambiguity remained unresolved. Assigning the $\rho\gamma$ structure to the $\eta(1440)$, a comparatively large ratio of $(0.188 \pm 0.056)\%$ is derived from the results of Coffman et al. [30] and of Bolton et al. [23]. Combining [30] and [24] one obtains $(0.091 \pm 0.026)\%$, in very good agreement with our result. Our result is less precise than those obtained from J/ψ radiative decays. However, the signal observed in $\bar{\mathrm{p}}\mathrm{p}$ annihilation does not suffer from the $\eta(1405)/f_1(1420)$ uncertainty and makes the assumption plausible that also the signal from J/ψ decays originates from the radiative decay $\eta(1405) \to \pi^+\pi^-\gamma$. Our result also has the advantage that the partial widths $\Gamma_{\pi^+\pi^-\gamma}$, $\Gamma_{\pi^+\pi^-\eta}$ and $\Gamma_{\mathrm{K}\bar{\mathrm{K}}\pi}$ refer to the same low–mass structure of the $\eta(1440)$ complex.

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