Evidence for a $\pi\eta$-P-wave in $\bar{p}p$-annihilations at rest into $\pi^0\pi^0\eta$

Crystal Barrel Collaboration

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A partial wave analysis is presented of two high-statistics data samples of protonium annihilation into $\pi^0\pi^0\eta$ in liquid and 12 atm gaseous hydrogen. The contributions from the $^1S_0$,$^3P_1$ and $^3P_2$ initial atomic fine structure states to the two data sets are different. The change of their fractional contributions when going from liquid to gaseous H_2 as calculated in a cascade model is imposed in fitting the data. Thus the uncertainty in the fraction of S-state and P-state capture is minimized. Both data sets allow a description with a common set of resonances and resonance parameters. The inclusion of a $\pi\eta$ P-wave in the fit gives supportive evidence for the $\hat{\rho}(1405)$, with parameters compatible with previous findings.

Meson resonances with exotic quantum numbers identifying their non-$q\bar{q}$ nature are of special interest in meson spectrocopy. Particular attention has been given to the $\pi\eta$ system which appears to be resonant in the partial wave with orbital angular momentum ℓ=1 carrying exotic quantum numbers. First evidence for an exotic $\pi\eta$ resonance was claimed by the GAMS collaboration [1] in the charge exchange reaction $\pi^- p \to \eta\pi^0$ n; the findings were, however, ambiguous in later analyses [2]. Contributions from an exotic $\pi\eta$ P-wave were also reported from VES [3]. At KEK [4], observation of a $\pi\eta$ resonance was claimed but the mass and width coincided with the $a_2(1320)$ parameters, and a feedthrough from the dominant D-wave into the P-wave cannot be excluded. Evidence for a resonant $\pi\eta$ P-wave was reported at BNL with parameters which differ significantly from those of the $a_2(1320)$ [5]. In all these studies the $\pi\eta$ P-wave is seen in a forward-backward asymmetry of the $\eta\pi$-system produced in $\pi^- p \to \eta\pi^- p$ or $\pi^- p \to \eta\pi^0 n$ which evidences interference between even and odd $\eta\pi$ partial waves. Contributions from odd partial waves were already reported in [6] but with no resonant phase motion in the $\pi\eta$ P-wave.

The Crystal Barrel Collaboration found evidence for an $I^G(J^{PC}) = 1^-(1^{-+})$

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exotic state [7] with mass and width of $1400 \pm 20_{stat} \pm 20_{syst}$ MeV and $310 \pm 50_{stat}(^{+50}_{-30})_{syst}$ MeV, respectively. The resonance was produced in the reaction $\bar{p}n \rightarrow \pi^- \pi^0 \eta$ obtained by stopping antiprotons in liquid deuterium. On the other hand, data on $\bar{p}p$ annihilation at rest in liquid hydrogen (LH_2) into $\pi^0\pi^0\eta$ had been used by us [8] and by Bugg and coworkers [9] to search for this state. These analyses found strong evidence for a new scalar isovector resonance, the $a_0(1450)$. A weak $\pi\eta$ P-wave contribution was found but there was no evidence for a resonant phase motion. Neither analyses included contributions of annihilations from atomic P-states. In this letter we report on an analysis of data on $\bar{p}p$ annihilation in liquid and in gaseous H_2 at 12 atm. In H_2 gas, the probability of annihilation from atomic P-states is much larger [10] and can certainly no longer be neglected. The addition of data for annihilation in H_2 gas and the inclusion of P-state capture in the analysis will now give supportive evidence in favor (and no longer against) a resonant P-wave in the $\pi\eta$ system.

The data we discuss here were recorded with the Crystal Barrel detector at LEAR. It has been described in detail elsewhere [11], therefore only a short summary is given. A beam of slow antiprotons was extracted from LEAR; the $\bar{p}$'s stopped in a target at the center of the detector. Liquid and gaseous hydrogen (LH_2 and $G^{(12\,\mathrm{atm})}H_2$) have been used as targets. The target was surrounded by a pair of cylindrical multiwire proportional chambers (PWC's) and a cylindrical jet drift chamber (JDC) with 23 layers. The JDC was surrounded by a barrel consisting of 1380 CsI(Tl) crystals in pointing geometry. The CsI calorimeter covers the polar angles between 12° and 168° with full coverage in azimuth. The overall acceptance for shower detection is $0.95 \times 4\pi$ sr. Typical photon energy resolutions are σ_E=2.5% at 1 GeV, and $\sigma_{\Phi,\Theta} = 1.2°$ in both the polar and azimuthal angles.

From previous run periods a high-statistics data sample on $\bar{p}p$ annihilation in a LH_2 target is available. For the present analysis we recorded data on $\bar{p}p$ annihilation in gaseous hydrogen at 12 atm, again with an *all neutral* trigger requiring no hits either in the PWC's or in the JDC. After rejection of events with residual charged particles we were left with 13 239 623 all neutral events. In addition we recorded *minimum-bias* data, only requiring an antiproton stopping in the target. These data are used for normalisation of the $\pi^0\pi^0\eta$ branching ratio.

As a first step we select events with exactly six electromagnetic showers in the calorimeter with an energy deposit in the central crystal exceeding 10 MeV. This cut reduces spurious photons due to shower fluctuations. No accepted photon should have its maximum energy deposit in a crystal adjoining the beam pipe since part of its energy may have escaped detection. Subsequently the data are subjected to a series of kinematic fits. In a first step we impose energy and momentum conservation by applying a four-constraint

(4C) fit; events with a probability for the $\bar{p}p \to 6\gamma$ hypothesis exceeding 1% are kept. This sample is then submitted to a 6C kinematic fit to the hypothesis $\bar{p}p \to \pi^0\pi^0 2\gamma$ and finally to a 7C kinematic fit to the hypothesis $\bar{p}p \to \pi^0\pi^0\eta$. Events having a probability to combine the photons to $\pi^0\pi^0\eta$ of less than 10% are rejected so as to minimize background contaminations from $\pi^0\pi^0\pi^0$, $\pi^0\eta\eta$ or $\pi^0\pi^0\omega$ (where one soft photon is missing in the decay $\omega \to \pi^0\gamma$). In addition we applied an anticut at 1% in the confidence level on the most frequent $3\pi^0$ final state. These cuts lead to 269 087 events of the type $\bar{p}p \to \pi^0\pi^0\eta$. The background contribution determined from Monte-Carlo simulations is less than 1%. Quality and statistics are identical to the data set we have for this reaction from annihilation in liquid H_2.

The $\pi^0\pi^0\eta$ decay branching ratio is calculated using

$$BR(\bar{p}p \to \pi^0\pi^0\eta) = \frac{N_{\pi^0\pi^0\eta}}{N_{AN-trig}} \times \frac{N_{MB}}{N_{AN}} \times \frac{1}{\epsilon} \tag{1}$$

where $N_{\text{AN-trig}}$ represents the number of triggered all neutral data and $N_{\pi^0\pi^0\eta}$ is the number of reconstructed events corrected by the decay probabilities for $P(\pi^0 \to \gamma\gamma) = 0.988$ and $P(\eta \to \gamma\gamma) = 0.3925$. The fraction of all neutral events in $\bar{p}p$ annihilations is determined by selecting $\pi^0\pi^0$-events in all neutral triggered data and by comparing to a selection of the same channel in minimum-bias-triggered data. We find $N_{AN}/N_{MB}=(3.32 \pm 0.28)\%$. The detection efficiency of the electromagnetic calorimeter and its performance were determined by Monte-Carlo simulations. The simulated events passed the same selection chain as real data. The Monte-Carlo Dalitz plot was used to define an acceptance correction function. It proved to be uniform to better than $\pm 4.5\%$ except for edge bins. A mean detection efficiency of $\epsilon_{\text{gas}}=(28.7 \pm 1.7)\%$ was derived. Thus the branching ratio for the reaction $\bar{p}p \to \pi^0\pi^0\eta$ for annihilations in gaseous hydrogen was determined to be

$$BR(\bar{p}p \to \pi^0\pi^0\eta\ ) = (6.14 \pm 0.67) \times 10^{-3}. \tag{2}$$

This value is similar to the values found in LH_2, $(6.7 \pm 1.2) \times 10^{-3}$ [8] and $(6.5 \pm 0.72) \times 10^{-3}$ [12], respectively.

The $\pi^0\pi^0\eta$ Dalitz plot for antiprotons annihilating in gaseous H_2 is shown in figure 1, and the $\pi^0\pi^0$- and $\pi^0\eta$-mass projections including fit results in figure 2 and figure 3, respectively. The data with antiprotons stopping in liquid H_2 were presented in [8] (280 000 events).

We first comment on general features of the data. The most prominent signals are a sharp-edged band structure due to the $a_0(980)$ and a w-shaped structure at the $a_2(1320)$ mass. In the $\pi^0\pi^0$mass projection (see figure 3) the intensity rises slowly and peaks at the $f_0(980)$; then, at the $K\bar{K}$ threshold, the intensity falls off rapidly. The high-mass peak is not due to the $f_2(1270)$ but is

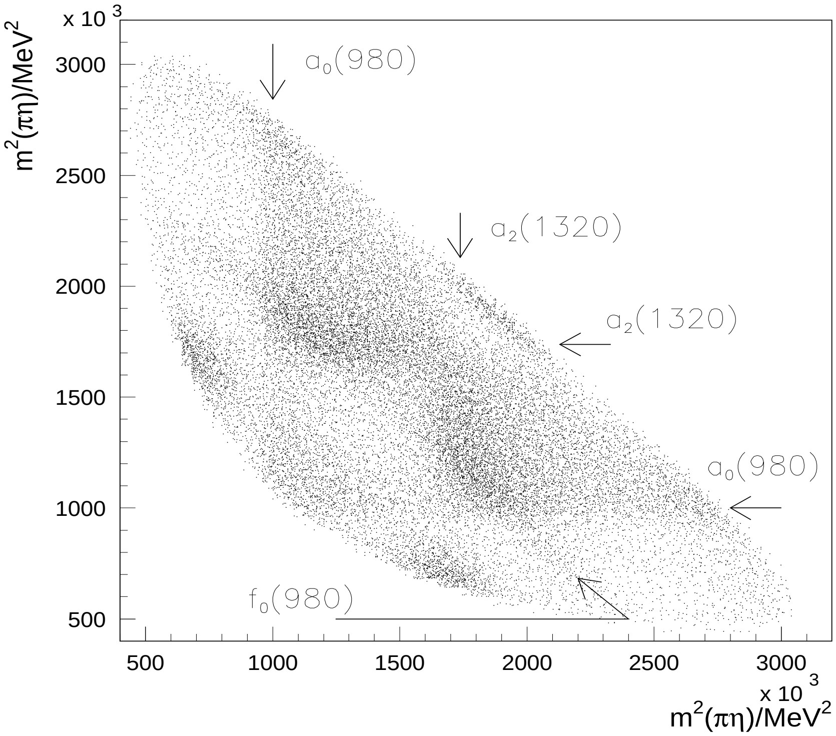

Fig. 1. Dalitz plot of $\bar{p}p$ annihilations at rest into $\pi^0\pi^0\eta$ for antiprotons stopping in gaseous hydrogen at 12 atm (2 entries per event).

a reflection from the $a_0(980)$ and $a_2(1320)$ decay angular distributions. The $\eta\pi^0$-mass distribution along the $a_0(980)$ band exhibits a slight depletion at a squared mass of $2.2\,\mathrm{GeV}^2$. This depletion requires the introduction of the second isovector state, the $a_0(1450)$ [8]. The $a_0(1450)$ in the vertical band interferes destructively with the $a_0(980)$ in a horizontal band and vice versa.

We now turn to a discussion of the partial wave analysis. The atomic cascade of antiprotons captured by protons to form protonium atoms plays an important role in this analysis. Therefore a short outline of the cascade processes is given.

Antiprotons stopping in H_2 are captured by protons and form $\bar{p}p$ atoms in high-n Rydberg states. In collisions with neighbouring H_2 molecules, Stark mixing between levels of different orbital angular momenta occurs leading to annihilation from high-n S- and P-states. The fractional contributions of S-state and P-state capture depends on the target density and on the specific channel under consideration. Globally, $(13 \pm 2)\%$ of all annihilations proceed via atomic P-states when antiprotons are stopped in liquid H_2 [10]. The neglect of the small fraction P-state capture is well justified when strong signals are observed in the final state. The inclusion of P-state capture would then increase the number of free parameters in the partial wave analysis and often results in unphysical solutions for the P-state annihilation dynamics. In this paper we present data on p̄p annihilation at rest into $\pi^0\pi^0\eta$ in liquid and in pressurised hydrogen gas at 12 atm. In H_2 gas we expect a significant contribution from P-state capture. The two sets of data thus give better information to include annihilation from S- and P-states in the analysis. Of course, the inclusion of P-state capture not only gives access to P-state annihilation dynamics but also alters the fit results for the data set taken in LH_2 which would be obtained when P-state capture is neglected.

While the exact fraction of P-state capture for a specific final state is unknown, at least the ratios with which capture rates from S-states and P-states change can be estimated reliably when the target density is varied. These ratios can be imposed in the partial wave analyses thus minimizing the uncertainties due to the atomic cascade which precedes annihilation. From now on we will refer to these ratios as *cascade ratios*. A cascade ratio of 0.564 for the $^1S_0$ level of the p̄p system indicates that the contribution of the $^1S_0$ state to the annihilation process decreases by the factor 0.564 when the target is changed from liquid H_2 to 12 atm H_2 gas. The cascade ratios are assumed not to depend on the specific final state.

Batty [10] determined these cascade ratios for the contributions of individual protonium states to the annihilation process in a model of the protonium cascade. The model allows one to calculate the yield of X-rays emitted during the atomic cascade and the fraction with which atomic levels contribute to annihilation. The hadronic widths of the atomic states are partially known from experiment, partially from model calculations. But since the agreement between data and model calculation is good, the calculation can be trusted also for those hadronic widths which are not measured directly. The free parameters of the cascade model are determined by a fit to experimental branching ratios for two-body annihilations determined over a wide range of target densities.

The same kind of ratios were determined also by Gastaldi and Placentino [13] for p̄p annihilation in liquid H_2 and gaseous H_2 at various densities. They do not use a cascade model but only known ratios of branching ratios. From their curves we estimated the ratios we should expect for 12 atm H_2 gas, and also estimated the errors. Of course, this procedure is crude but may help to convince us that the cascade ratios are reliably estimated. We shall use only the cascade ratios as calculated in the cascade model of Batty.

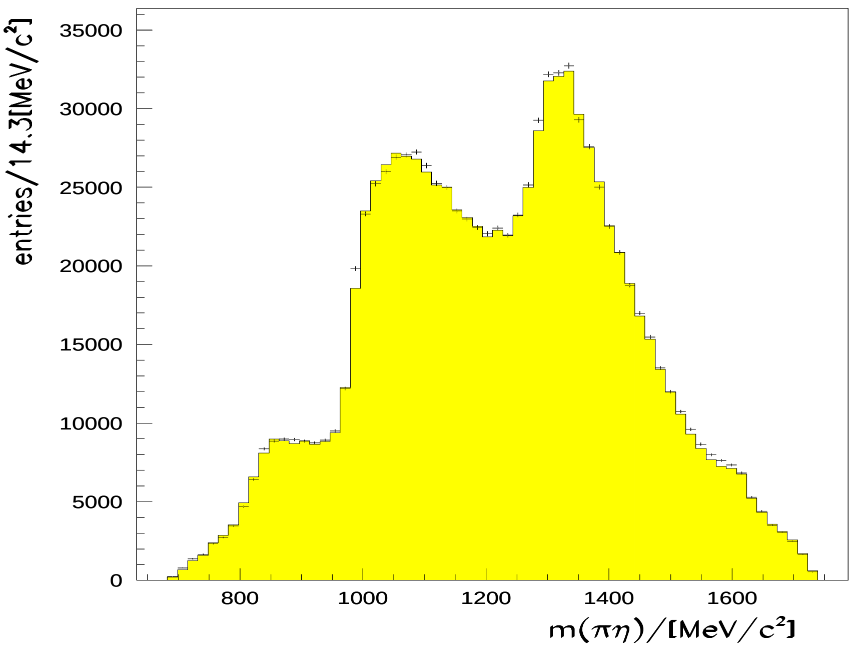

Fig. 2. *The* $(\eta\pi)$ *mass distribution for* $\bar{p}p \rightarrow \pi^0\pi^0\eta$ *for data from gaseous hydrogen. The shaded area represents the fit.*

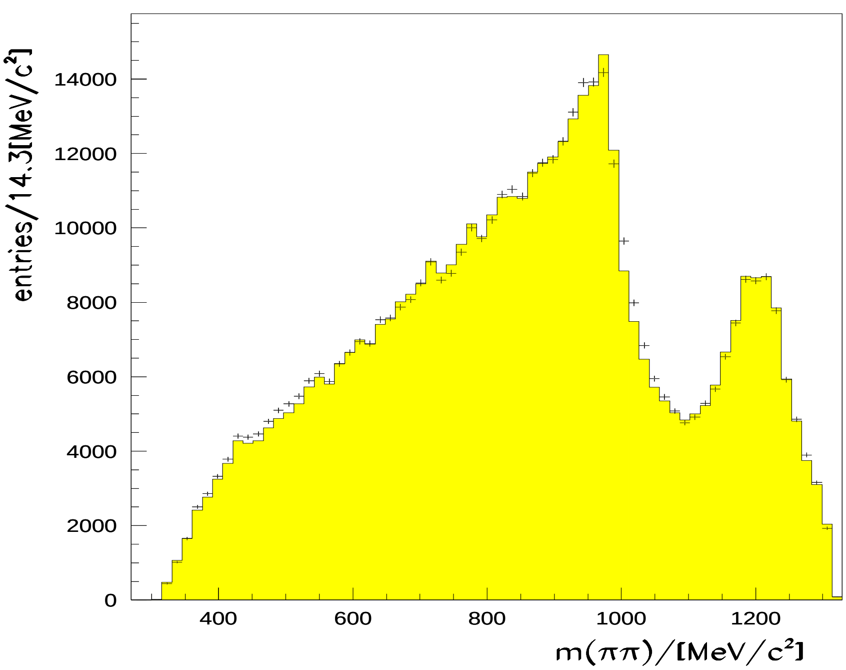

Fig. 3. *The* $\pi\pi$*-mass distribution for* $\bar{p}p \rightarrow \pi^0\pi^0\eta$ *for data from gaseous hydrogen. The shaded area represents the fit.*

$^{2S+1}L_J$	$^1S_0$	$^3P_1$	$^3P_2$
Batty [10]	$0.564 \pm 0.062 \pm 0.080$	$4.961 \pm 1.605 \pm 0.692$	$4.046 \pm 1.309 \pm 0.582$
Gastaldi [13]	0.60 ± 0.10	$2.0^{+3.0}_{-1.4}$	5.0 ± 3.0

Table 1
Ratio of annihilation rates for annihilation in LH_2 and 12 atm H_2 gas from specific initial states of the protonium atom. The first line shows two errors. The first one is the error due to uncertainties in the cascade parameters and in the branching ratios used to determine these constants; the second error gives the variation of the constants when the pressure is changed by ±3 atm. The second line shows estimated values and errors using $\bar{p}p$ annihilation branching ratios.

In Table 1 we give the cascade ratios for the 3 initial states from which annihilation into $\pi^0\pi^0\eta$ is allowed. These have the quantum numbers $^{2S+1}L_J = {}^1S_0$, $^3P_1$ and $^3P_2$.

The two $\pi^0\pi^0\eta$ Dalitz plots were analysed using an isobar model. The scalar $\pi^0\pi^0$ and $\pi^0\eta$ interactions are described in the K-matrix formalism using the P-vector approach of Aitchison [14]. The $\pi^0\pi^0$ scattering amplitude is constrained to be consistent with results on phase shift analyses of $\pi\pi$ interactions [15,16]. Tensor waves and the $\pi\eta$ P-wave are parametrized by relativistic Breit-Wigner amplitudes. The same model has been used to fit the Dalitz plot (also used here) for $\bar{p}$'s stopping in liquid H_2 [8]. Further details of the method can be found in [17] respectively.

In [8] P-state capture was neglected. In spite of this approximation we found a good description of the data with the following amplitudes:

- a scalar $\pi\pi$ wave with $f_0(980)$ and $f_0(1370)$
- a weak tensor $\pi\pi$ wave with $f_2(1275)$
- a scalar $\pi\eta$ wave with $a_0(980)$ and $a_0(1450)$
- a tensor $\pi\eta$ wave with $a_2(1320)$ and some $a_2(1650)$
- a weak non-resonant isovector $\pi\eta$ wave (or with a width of ~ 400 MeV or more)

First we demonstrate the need for P-state capture. If we fit both data sets with S-state capture alone the χ^2 is 14 200 for 5219 data points or 2.75 per degree of freedom. Obviously, S-state capture alone cannot describe the data with sufficient accuracy, it is necessary to introduce P-state capture. Now we impose the cascade ratios but allow them to vary freely within the limits given in Table 1. The best fit with free cascade ratios gives a χ^2/N_F of 1.33 which we find acceptable in view of the very large statistics ($\sim 550\,000$ $\pi^0\pi^0\eta$ events). The fit requires a resonant $\pi\eta$ P-wave with a finite width; the optimum is reached for M=1382 MeV and $\Gamma = 245$ MeV. The χ^2 gets worse by 149 when the $\pi\eta$ P-wave is chosen to be nonresonant (the width set to 1 GeV), and by 367 when the $\pi\eta$ P-wave is suppressed completely. However, the P-state capture rate for annihilation in liquid H_2 of $\sim 35\%$ derived from this fit seems high. However, these ratios are strongly correlated with the cascade ratios.

A reasonable fit (Fig. 2,3) with $\chi^2/N_F = 1.37$ is also obtained when the cascade ratios are fixed to the central values given by Batty (see Table 1). The $\pi\eta$ P-wave is then seen with a mass of 1350 MeV and a width of 270 MeV. The $^1S_0$ state contributes 92% of all annihilations in liquid and 60% of all annihilations in gaseous H_2 at 12 atm. The χ^2 difference for excluding the $\pi\eta$ P-wave is now 600.

Obviously, the cascade ratios play an important role in the interpretation of the data. Therefore we made a series of fits in which the cascade ratios were varied stochastically over a wide range (for $^1S_0$ from 0.5 to 1; for $^3P_1$ from 2.3 to 10; for $^3P_2$ from 0.8 to 10). Since the cascade ratios are correlated their effect on the results of the partial wave analysis is explored over a wider range than would be required minimally. All fits consistently required a resonant $\pi\eta$ wave. The extreme values we found were 1335 MeV to 1385 MeV for the mass and 130 MeV to 310 MeV for the width.

We conclude that there is evidence for the existence of a resonant $\pi\eta$ P-wave in the data which is called $\hat{\rho}(1405)$ in [18] in accordance with [7]. The statistical significance is weak if we allow comparatively large ($\sim$30%) P-state capture rates in liquid H_2. For fits with $\sim$10% P-state capture probabilities the evidence is much stronger. Independent of this uncertainty we find in all fits a resonant $\pi\eta$ P-wave and masses and widths lying in the range

$$M_{\hat{\rho}(1405)} = (1360 \pm\ 25)\text{MeV}$$
$$\Gamma_{\hat{\rho}(1405)} = (220 \pm\ 90)\text{MeV}$$

A relativistic Breit-Wigner amplitude is the simplest description of the $\pi\eta$ P-wave but may not be unique. With the data presented here we cannot exclude the possibility that the phase variation required in the fit could be introduced through threshold effects due to the opening of the $f_1(1285)\pi$ or $b_1(1235)\pi$ channel.

The $\hat{\rho}(1405)$ is produced at a very small rate ($\sim$ 1% of $\pi^0\pi^0\eta$ in liquid hydrogen) via the $^1S_0$ state but significantly ($\sim$ 4% of $\pi^0\pi^0\eta$ in gaseous hydrogen) from the $^3P_1$ state. This is a rather large rate considering the fact that the total contribution of the $^3P_1$ state is (20 to 25)%. In [7] we reported evidence for the $\hat{\rho}(1405)$ in $\bar{p}n \to \pi^-\pi^0\eta$ annihilation where the $\hat{\rho}(1405)$ production is larger from $^3S_1$ than from the $^1P_1$ states. We conjecture that the $\hat{\rho}(1405)$ is produced more abundantly from spin triplet states and not from spin singlet states.

A resonance with quantum numbers $J^{PC}=1^{-+}$ cannot possibly be a $q\bar{q}$ state; it is exotic. Since its isospin is I=1 it cannot be a glueball [19]. The two alternative interpretations are that the $\hat{\rho}(1405)$ is a hybrid [20], a state in which a color-octet $q\bar{q}$ system is neutralised in color by a constituent gluon; or it could be a four-quark state [21,22]. The latter possibility seems to be more likely: as a hybrid it would be a SU(3) octet state which is forbidden to decay into two SU(3) octet states since the orbital angular momentum requires antisymmetry, the SU(3) isoscalar factor symmetry with respect to the exchange of the π and the η meson [23]. A hybrid state could couple to the SU(3)-singlet component of the η. In this case the the $\hat{\rho}$ (1405) should decay prominantly into $\pi\eta'$. A study of the reaction $\bar{p}p \to \pi^0\pi^0\eta'$ did, however, not show any evidence for the $\hat{\rho}$ (1405) [24]. As a four-quark resonance it can be a SU(3) decuplet state with allowed coupling to two octet states. These arguments would suggest that the $\hat{\rho}$ (1405) is likely to be a four-quark state.

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