$\rho - \omega$ interference in $\bar{p}p$-annihilation at rest into $\pi^+\pi^-\eta$

Crystal Barrel Collaboration

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The $\pi^+\pi^-$ invariant mass distribution produced in $\bar{p}p$ annihilation at rest and recoiling against η mesons exhibits large interference between the amplitudes for $\rho\eta$ and $\omega\eta$ production. The interference can be quantitatively described within the framework of ρ-ω interference. We find full coherence between the $\rho\eta - \omega\eta$ production amplitudes and a vanishing relative production phase. The implications of this result for $\bar{p}p$ annihilation dynamics are discussed.

Charge symmetry is broken due to the small mass difference between up- and down-quarks. Hence the observed ρ and ω mesons are not isospin eigenstates, they both have isoscalar and isovector components. Thus ω mesons decay not only via their dominant $\pi^+\pi^-\pi^0$ decay mode but also into $\pi^+\pi^-$ [1]. In processes in which both ω and ρ^0 mesons are produced, the $\omega\to\pi^+\pi^-$ decay mode interferes with $\rho\to\pi^+\pi^-$ decays. The comparatively narrow ω with its rapidly changing phase leads thus to a characteristic interference pattern modifying the line shape of the ρ^0.

Perhaps the cleanest way to observe ρ-ω interference is to study e^+e^- annihilation into $\pi^+\pi^-$ in the ρ mass range. A clear kink at the ω mass is observed which is quantitatively described by ρ-ω interference [2]. The effect is well understood, at least at a phenomenological level. An excellent review of the field can be found in [3].

The emphasis of the present paper is not the demonstration of ρ-ω interference nor of the validity of the ρ-ω mixing scheme. Instead, we look for possible modifications which may occur due to the hadronic aspects of $\bar{p}p$ annihilation absent in e^+e^- annihilation. The absence of these effects (at the level of the precision achieved) constrains models of $\bar{p}p$ annihilation dynamics. Well suited for this investigation is the reaction

$$\bar{p}p\to\pi^+\pi^-\eta \tag{1}$$

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since the branching ratio $\bar{p}p \to \eta\omega$ is large and hence large interference effects can be expected.

The data for reaction (1) were collected with the Crystal Barrel detector at LEAR. This detector is well suited to measure channels with both charged and neutral particles in the final state. It has been described in detail elsewhere [4]; only a short summary will be given here.

The LEAR machine delivers a beam of 200 MeV/c antiprotons which are stopped in a liquid H_2 target at the center of the detector. The target is surrounded by a pair of cylindrical multiwire proportional chambers (PWC's) and a cylindrical drift-chamber (JDC) with 23 layers. The momentum resolution for charged particles is $\delta p/p = 6.5\%$ at 1 GeV/c. The JDC is surrounded by a barrel consisting of 1380 CsI(Tl) crystals in a pointing geometry. The CsI calorimeter covers the polar angles between 12° and 168° with full coverage in azimuth. The useful acceptance for shower detection is $0.95 \times 4\pi$ sr. Typical photon energy resolutions are $\sigma_E/E = 2.5\%$ at 1 GeV, and $\sigma_{\Phi,\Theta} = 1.2°$ in both the polar and azimuthal angles.

The data for the present analysis have been taken with a *two-prong trigger* requiring two hits per layer in two inner and two outer JDC-layers and with an open *minimum-bias trigger.* With these triggers, 13,697,820 *two-prong* and 822,493 *minimum-bias* events were recorded. The *minimum-bias* data were used for normalisation of the $\pi^+\pi^-\eta$ branching ratio, and were treated in exactly the same way as the *two-prong* data.

We require two good-quality tracks in the JDC and two photons with energy above 14 MeV. To avoid fake photons due to shower fluctuations, we require that each photon have at least 13 MeV in its central crystal. In addition, we reject events where the photon had its maximum energy deposition in a crystal adjacent to the beam pipe. These cuts yield 1,953,710 events. Subsequently the data are subjected to kinematic fitting to the hypothesis $\pi^+\pi^-2\gamma$ (4C) and then in a second step, to the $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\eta$, and $\pi^+\pi^-\eta'$ hypotheses (5C).

The $\gamma\gamma$ invariant mass spectrum for those events passing the $\pi^+\pi^-2\gamma$ fit shows clean π^0 's and η 's over a very small background. To extract the $\pi^+\pi^-\eta$ data, we placed a 10% confidence level cut in both the $\pi^+\pi^-2\gamma$ and $\pi^+\pi^-\eta$ fits. From these we have an upper limit on the background of 1.5% of the surviving 80,287 events. These events are assigned to reaction (1).

A Monte Carlo simulation based on the CERN program package GEANT was used to derive the detection efficiency. From the number of annihilations, the fraction of antiprotons stopping in the liquid H_2 target (0.96 ± 0.02), the number of $\pi^+\pi^-\eta$ events observed in the *minimum bias* data (6463 ev. $\pi^+\pi^-\pi^0$ and 720 ev. $\pi^+\pi^-\eta$) and the reconstruction efficiency, $(14.6 \pm 0.7)\%$ for $\pi^+\pi^-\pi^0$and

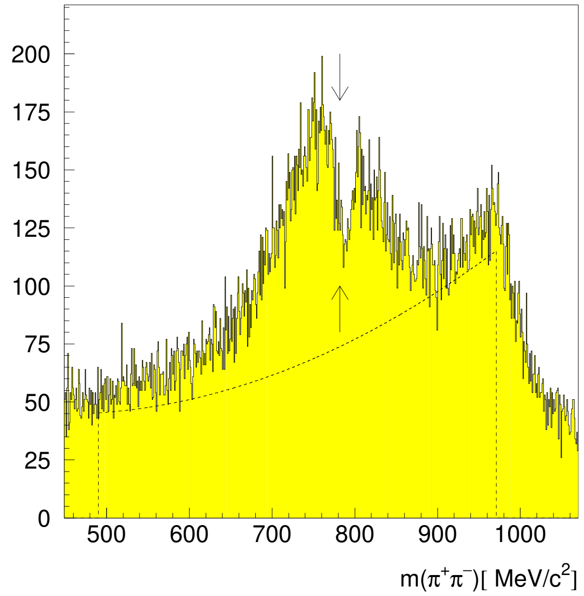

Fig. 1. $\pi^+\pi^-$ invariant mass in the reaction $\bar{p}p \to \pi^+\pi^-\eta$ in $\bar{p}p$ annihilation at rest. The arrows indicate the mass of the ω meson.

$(14.2 \pm 1.0)\%$ for $\pi^+\pi^-\eta$, we find branching ratios for $\bar{p}p$ annihilations at rest into $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\eta$ of

$$\mathrm{BR}(\bar{p}p \to \pi^+\pi^-\pi^0) = (58.2 \pm 4.3) \cdot 10^{-3}$$
$$\mathrm{BR}(\bar{p}p \to \pi^+\pi^-\eta) = (16.3 \pm 1.2) \cdot 10^{-3}$$

These numbers can be compared to previous measurements:

$$\mathrm{BR}(\bar{p}p \to \pi^+\pi^-\pi^0) = (69 \pm 4) \cdot 10^{-3} \quad [6]$$
$$\mathrm{BR}(\bar{p}p \to \pi^+\pi^-\eta) = (13.7 \pm 1.5) \cdot 10^{-3} \quad [15]$$

A more complete list of previous values can be found in Table 1.

In Fig. 1 we show the $\pi^+\pi^-$ invariant mass spectrum recoiling against an η meson from the reaction (1). A striking interference pattern is observed. The arrows indicate the mass of the ω. There is constructive interference below the nominal ω mass and destructive interference above. This pattern is expected when the $\rho\eta$ and $\omega\eta$ production amplitudes have about the same phase. There is obvious interest in studying this effect in more detail.

Due to the presence of ρ-ω interference the relativistic Breit-Wigner function for ρ^0-mesons has to be modified by an expression derived from the ρ-ω mixing matrix. Its off-diagonal matrix element $<\omega|M|\rho>$ is an empirical parameter. Its magnitude $\delta = <\omega|M|\rho> /(m_\rho + m_\omega) = 2.5 \pm 0.2$ MeV is derived from ρ-ω interference in e^+e^- annihilation [3]. Hence we write the modified Breit-Wigner "S" as:

$$S = p \cdot q \left| \mathrm{BW}_\rho \left(1 + \frac{\mathrm{BW}_\omega}{\mathrm{BW}_\rho} \cdot \epsilon_{\mathrm{coh}} \cdot e^{i\beta} \cdot \frac{e^{i\varphi}}{m_\omega^2 - m_\rho^2 - i(m_\omega \Gamma_\omega - m_\rho \Gamma_\rho(s))} \right) \right|^2 \quad (2)$$

where ϵ_{coh} and β are fit parameters. We have:

$$\mathrm{BW}_\alpha = A_\alpha \frac{D_1(p)\, m_\alpha\, \Gamma_\alpha \frac{1}{\rho(m_\alpha^2)} \cdot B_1^\alpha(q, q_\alpha)}{m_\alpha^2 - s - i\, m_\alpha\, \Gamma_\alpha \frac{\rho(s)}{\rho(m_\alpha^2)} \cdot B_1^\alpha(q, q_\alpha)^2}$$

BW_α is a Breit-Wigner for resonance $\alpha = \rho, \omega$ with a production amplitude A_α. B_1^α is a Blatt-Weisskopf factor with ℓ=1 for resonance α:

$$\begin{aligned}
B_1^\alpha(q, q_\alpha) &= \frac{D_1(q)}{D_1(q_\alpha)} \\
D_1(q) &= \frac{q}{p_r} \sqrt{\frac{2}{(\frac{q}{p_r})^2 + 1}} \qquad p_r = 197.3 \text{ MeV/c} \\
p &= \frac{\left[(M_{\bar{p}p}^2 - (\sqrt{s} + m_\eta)^2) \cdot (M_{\bar{p}p}^2 - (\sqrt{s} - m_\eta)^2) \right]^{1/2}}{2 M_{\bar{p}p}} \\
q &= \frac{\left[s - 4 m_{\pi\pm}^2 \right]^{1/2}}{2} \qquad q_\alpha = \frac{\left[m_\alpha^2 - 4 m_{\pi\pm}^2 \right]^{1/2}}{2} \\
\rho(s) &= \frac{1}{\sqrt{s}} \sqrt{s - 4 m_{\pi\pm}^2}
\end{aligned}$$

The phase $\varphi = 76.4°$ is found from the relation

$$\tan\varphi = \frac{m_\omega \Gamma_\omega - m_\rho \Gamma_\rho(m_\omega^2)}{m_\omega^2 - m_\rho^2}.$$

$|A_\omega/A_\rho|^2$ is identified with the ratio of $\bar{p}p$ annihilation frequencies into $\eta\omega$ and $\eta\rho$. With BR($\bar{p}p \to \eta\omega$) = $(1.51 \pm 0.12) \cdot 10^{-2}$ [9] and our value for $\bar{p}p \to \eta\rho$ (see below) we find $|A_\omega/A_\rho|^2 = 3.9 \pm 0.4$.

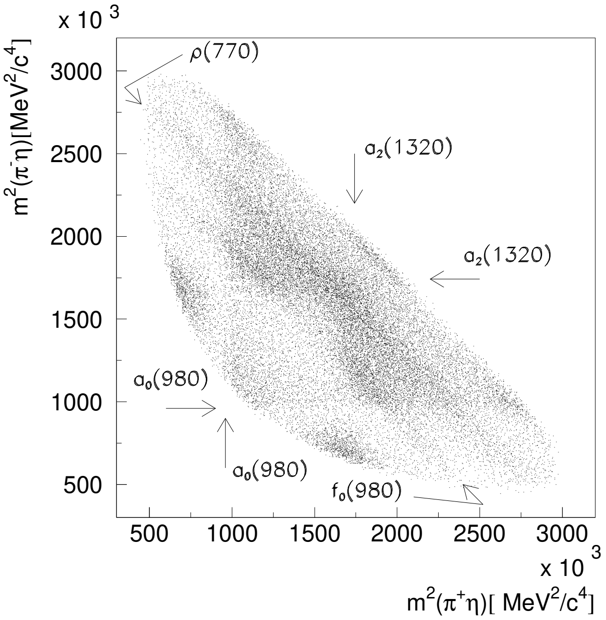

Fig. 2. $\pi^+\pi^-\eta$ Dalitz-plot for antiprotons stopping in a liquid H_2 target.

Due to the considerable background under the ρ, one cannot simply fit Fig. 1 to obtain BR($\bar{p}p \to \eta\rho$). Rather it is necessary to fit the entire $\pi^+\pi^-\eta$ Dalitz plot which is presented in Fig. 2. It is quite similar to the $\pi^0\pi^0\eta$ Dalitz plot observed by us in its 6γ final state [10]. New here is the clear ρ band which was absent in the $\pi^0\pi^0$ invariant mass. In addition the amplitude for ${}^1\mathrm{S}_0(\bar{p}p) \to a^{\pm}_{0,2}\pi^{\mp}$ has the opposite sign of the ${}^1\mathrm{S}_0(\bar{p}p) \to a^0_{0,2}\pi^0$ from $\eta\pi^0\pi^0$.

The most prominent structure in the Dalitz plot is due to the charged $a_2^{\pm}(1320)$ mesons. Their W-shaped angular distributions (indicating annihilation from the ${}^1\mathrm{S}_0$ state) interfere and are responsible for the characteristic pattern already seen in $\pi^0\pi^0\eta$. A partial wave analysis of the latter reaction was reported in [10]. A clear step is seen at the $\overline{\mathrm{K}}\mathrm{K}$ threshold evidencing the presence of the $a_0(980)$. Its band has a depletion at about 2.2 GeV^2 which requires (as in the case of the $\pi^0\pi^0\eta$ data) introduction of a second scalar $\pi\eta$ resonance, of the $a_0(1450)$. The diagonal labeled $\rho(770)$ exhibits contributions from $\rho\eta$.

In this letter we present the results of a simplified partial wave analysis taking into account only S-state annihilation. P-state capture is included in order to estimate the systematic error of our final results. However the results on ρ-ω interference do not depend on details of the partial wave analysis.

The contributions from the ${}^1\mathrm{S}_0$ initial state to the $\pi^+\pi^-\eta$ and $\pi^0\pi^0\eta$ final states are related by Clebsch-Gordan coefficients. We thus can take over the poles from solution (A) from [10]. There are only two new contributions: ${}^3\mathrm{S}_1 \to \rho^0\eta$

$\mathrm{BR}(\bar{p}p \to \pi^+\pi^-\eta)$	$\mathrm{BR}(\bar{p}p \to \rho\eta)$		Reaction
$(13.8 \pm 1.7) \cdot 10^{-3}$	$(50 \pm 14) \cdot 10^{-4}$	[8]	$\bar{p}p \to 2\pi^+2\pi^-(\pi^0)$
$(15.1\ ^{+1.7}_{-2.1}) \cdot 10^{-3}$	$(64 \pm 14) \cdot 10^{-4}$	[7]	$\bar{p}p \to 2\pi^+2\pi^-(\pi^0)$
–	$(22 \pm 17) \cdot 10^{-4}$	[11]	$\bar{p}p \to 2\pi^+2\pi^-(\pi^0)$
–	$(53\ ^{+20}_{-\ 8}) \cdot 10^{-4}$	[12]	$\bar{p}p \to \pi^+\pi^-\gamma\gamma$
$(13.5 \pm 1.7) \cdot 10^{-3}$	$(96 \pm 16) \cdot 10^{-4}$	[13]	$\bar{p}p \to \pi^+\pi^-\gamma\gamma$
$(17.05 \pm 1.68) \cdot 10^{-3}$	$(33 \pm 9) \cdot 10^{-4}$	[14]	$\bar{p}p \to 2\pi^+2\pi^-(\pi^0)$ and $\bar{p}p \to 2\pi^+2\pi^-\gamma$
$(16.3 \pm 1.2) \cdot 10^{-3}$	$(38.7 \pm 2.9) \cdot 10^{-4}$	(this work)	$\bar{p}p \to \pi^+\pi^-\gamma\gamma$
	$(39.7 \pm 3.4) \cdot 10^{-4}$		average [8,7,11], this work

Table 1
Branching ratios for $\bar{p}p$ annihilation into $\pi^+\pi^-\eta$ and $\rho\eta$. The (π^0) indicates an unobserved π^0.

and ${}^3\mathrm{S}_1 \to a_2^{\pm}(1320)\pi^{\mp}$. Of particular interest for the present work is the branching ratio for $\bar{p}p \to \eta\rho$ for which ambiguous results have been reported in the literature. Our result is compared to previous results in Table 1.

The fit to the data is done in iterations. The Dalitz plot fit uses bin sizes of 0.052 GeV^2. This is not sufficient to extract reliable parameters on ρ-ω interference . Therefore we fit the Dalitz plot with approximate ρ-ω interference parameters. The fit gives amplitudes and phases for ${}^3\mathrm{S}_1 \to \rho^0\eta$ and ${}^3\mathrm{S}_1 \to a_2^{\pm}(1320)\pi^{\mp}$ with $\mathrm{BR}(\bar{p}p \to \rho\eta)/\mathrm{BR}(\bar{p}p \to a_2\pi) \approx 4/1$. The amplitude for ${}^3\mathrm{S}_1 \to \rho^0\eta$ is then set to zero. The result of this fit is shown in Fig. 3 together with a polynomial of second order which is assumed to represent the background under the ρ^0. We find only a small difference in the background when taking the interference between ${}^3\mathrm{S}_1 \to \rho^0\eta$ and ${}^3\mathrm{S}_1 \to a_2^{\pm}(1320)\pi^{\mp}$ into account or not.

The difference between data and background is fitted with eqn. (2) folded with a experimental resolution of $\sigma = (7.6 \pm 0.9)$ MeV. We find

$$\begin{aligned} \epsilon_{\mathrm{coh}} &= 1.14 \pm 0.15 \pm 0.13 \\ \beta &= (-5.4 \pm 1.8 \pm 3.9)^\circ \end{aligned}$$

where the systematic errors are estimated from various fits to the $\pi^+\pi^-\eta$ Dalitz

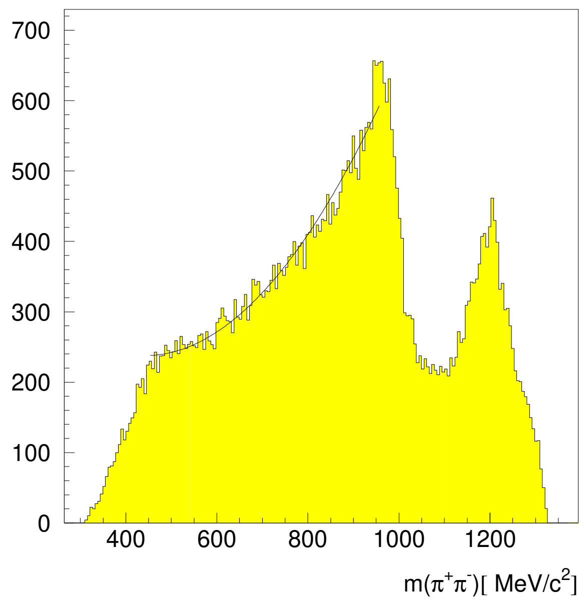

Fig. 3. $\pi^+\pi^-$ mass projection, $\rho(770)$ amplitude removed (see text).

plot including or excluding P-state capture.

Calculating an average value of Table 1 we get BR($\bar{p}p\to\rho\eta$) = $(40.5\pm5.8)\cdot10^{-3}$ and a coherence parameter of $\epsilon_{\rm coh} = 1.16 \pm 0.15 \pm 0.13$. The phase itself is independent of the ratio $|A_\omega/A_\rho|$ and of the branching ratio BR($\bar{p}p\to\rho\eta$).

The results are fully consistent with the hypothesis of full coherence and relative real phase between ρ and ω. The relative phase is in accordance with results we obtained in ρ-ω interference in their $\eta\gamma$ decay mode [16].

Before we discuss effects which might change the interference pattern we give a short outline of the experimental situation in which $\bar{p}p$ annihilation at rest occurs. Antiprotons stopping in liquid H_2 are captured by the Coulomb field of protons thus forming protonium atoms in high Rydberg states. Due to annihilation, the atomic states acquire a hadronic width. These widths are described very successfully in potential models of $\bar{p}p$ interactions, see e.g. [17]. In collisions with neighbouring atoms, large electric fields mix the angular momentum states leading to annihilation from S-states (with zero orbital angular momentum between proton and antiproton) [18]. Indeed, approximately 88% of all annihilations proceed via S-state annihilation [19]. The two annihilation modes $\omega\eta$ and $\rho\eta$ require negative C-parity of the initial state; hence $\bar{p}p\to\rho\eta$ and $\omega\eta$ comes dominantly from the $^3S_1$ protonium state. However the protonium states have no defined isospin and at large distances isoscalar and isovector components are relatively real and equal in amplitude. At short distances pion exchange becomes important and the $\bar{p}p$ and $\bar{n}n$ systems may mix. Different isoscalar and isovector annihilation potentials may lead to a non-zero phase between the $I = 0$ and $I = 1$ parts of the wave function. This is important for ρ-ω interference since annihilation into $\omega\eta$ proceeds via the isoscalar part of $\bar{p}p$ annihilation, $\rho\eta$ via the isovector part. The interference of the $\rho\eta$ and $\omega\eta$ amplitudes is therefore sensitive to the relative phase between $I = 0$ and $I = 1$.

Potential models which describe successfully the total width of protonium states predict a phase between $I = 0$ and $I = 1$ which depends on the p-$\bar{\text{p}}$ separation. In the range between 1.0 fm and 1.4 fm in which annihilation is supposed to take place this phase varies from -83° to -62° for typical annihilation potentials [20,21], the values given here were extracted from Fig. 1 in [22]. The models thus predict that there should be a global non-vanishing phase between $\rho\eta$ and $\omega\eta$ production amplitudes. Since the actual value of the phase depends on the p-$\bar{\text{p}}$ separation and the annihilation probability extends over a wide range, the amplitude of the interference should be reduced or the interference might even be washed out completely.

In quark models [23], all annihilation modes of a given atomic state into mesons belonging to the same meson nonets (here $\bar{p}p \to$vector plus pseudoscalar meson) have the same phase; hence from quark models we expect a similar interference pattern as in $e^+ e^-$ annihilation. The experimental results, $\epsilon_{\text{coh}} \approx 1$ and $\beta \approx 0$, indicates, that the quark model description of the $\bar{p}p$-annihilation process should be favoured compared to models based on annihilation potentials.

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