Absence of Discrete s-Channel Resonances in $\bar{p}p$ Interactions at Intermediate Energies

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We give new experimental results on ρ/ω interference and two-body cross sections in $\bar{p}p$ annihilation at 2.3 GeV/c. These are used, together with ρ/ω interference results from lower energies, to argue that the annihilation process is not mediated by discrete s-channel mesonic resonances in the mass range 2.1–2.6 GeV.

A special characteristic of $\bar{p}p$ interactions is the large number of open channels. This gives rise to strong attenuation of the incident wave with the lowest partial waves undergoing complete absorption and leading to final states of large multiplicity. Hence two-body final states are emitted primarily from a narrow range of incident impact parameter, bounded on the one hand by the range of the interactions and on the other by a radius characteristic of strong absorption to multibody final states.[1] So, in terms of partial waves, we expect two-body production to be dominated by a small number of angular-momentum states. Therefore, to establish a case for the production of two-body final states via discrete s-channel meson resonances, it is not sufficient to show that these states are dominated by a few J values. Rather, it is necessary to determine relative phases as well as magnitudes for the amplitudes or to observe a cross-section enhancement in a state of particular s-channel internal quantum numbers.

On the other hand, if, instead of discrete s-channel resonances, there are many overlapping such resonances, then these might be arranged in such a way that the smooth s dependence characteristic of t-channel exchange mechanisms is observed. This is the duality[2] postulate, which implies many constraints between amplitudes. In this case we would expect to observe only a slow variation of the relative phase of inelastic amplitudes as a function of energy, and a t-channel, rather than an s-channel, factorization of amplitudes, showing no preference for particular s-channel quantum numbers.

In this note we present evidence on relative phases and factorization which indicates that $\bar{p}p$ annihilations at intermediate energies are not mediated by individual s-channel resonances.[3] Specifically, the relative magnitude and phase of the $\omega\pi\pi$ $(G=-1)$ and $\rho\pi\pi$ $(G=+1)$ amplitudes are seen to be essentially constant over a broad energy range.[4] In addition, a crude t-channel factorization seems to hold for a number of two-meson final states.[5] The new data were obtained from a 6-event/μb exposure of 2.3-GeV/c antiprotons in the Argonne 30-in. hydrogen bubble chamber at the zero gradient synchrotron. The film was automatically scanned and measured by the POLLY II system[6] to yield a sample of 340 000 events of all multiprong topologies. Since this is the first bubble-chamber experiment to utilize automatic scanning, careful checks of the data were made.[7] For example, it was shown that the efficiency of the automatic scanning was greater than 95%.

In an earlier experiment,[8] we reported evidence for ρ/ω interference in the 2π-decay mode for the annihilation channels

$$\bar{p}p\to\rho^0\pi^+\pi^- \tag{1}$$

and

$$\bar{p}p\to\omega^0\pi^+\pi^- \tag{2}$$

over the momentum range 1.26–1.65 GeV/c. By using the branching-ratio determination from recent photoproduction experiments[9] that $\Gamma(\omega\to2\pi)/\Gamma(\omega\to3\pi)$ is $(2.8\pm0.6)\%$, the analysis of our previous experiment requires that the $\omega\pi\pi$ $(G=-1)$ and $\rho\pi\pi$ $(G=+1)$ amplitudes have a coherence[10] greater than 60% and that the ρ/ω relative phase in the 2π decay channel is near 90°.[11]

An identical kind of analysis has been carried out with the new data at 2.3 GeV/c. 6297 events were consistent with the four-constraint 4π final state, and the relevant part of the mass spectrum is shown in Fig. 1(a). The resolution was measured to be 10 MeV full width at half-maximum. When ρ/ω interference is included in the fit to the mass spectrum, the value of χ^2 decreases

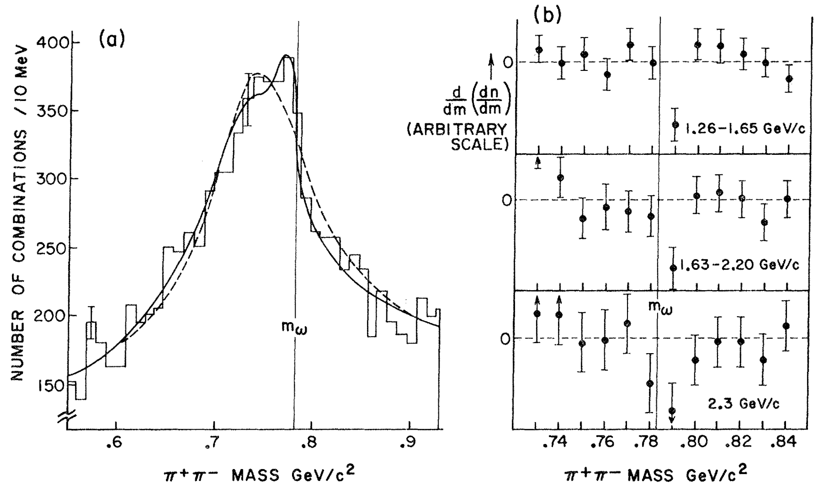

FIG. 1. (a) Part of the mass spectrum (dn/dm) of $\pi^+\pi^-$ from the reaction $\bar{p}p \to 4\pi$ at 2.3 GeV/c. The dashed curve shows a best fit with ρ^0 plus incoherent background ($M = 752 \pm 3$ MeV, $\Gamma = 126 \pm 20$ MeV). The solid curve is the best fit when a partially coherent $\omega \to 2\pi$ signal interferes with the ρ^0 ($M = 753 \pm 5$ MeV, $\Gamma = 160 \pm 30$ MeV). (b) The slopes of the $\pi^+\pi^-$ mass spectra $[(d/dm)(dn/dm)]$ from Refs. 8 and 13 and from the present experiment. Each shows a very pronounced dip near the ω mass, corresponding to a 90° phase difference.

by 17 for the addition of two degrees of freedom —a statistical significance[12] corresponding to 3.7 standard deviations. Assuming the above value for the $\omega \to 2\pi$ branching ratio,[9] we find that the ρ/ω coherence is large (> 50%) and that the observed relative phase in the 2π decay channel is in the range 75°–105°, i.e., the relative phase is the same to within 15° as it was at lower energies and in the intermediate-energy data of Chapman *et al.*[13] [see Fig. 1(b)]. In addition to the lower limit on the coherence, we note that the ratio of the cross sections for the two channels is energy independent to within about 20% (Table I). By considering resonance-background interference effects, we conclude the following:

(1) There is no isolated s-channel resonance of unique G parity in the same angular-momentum state as the background and with an amplitude more than about 25% of the background. If there were, the phase of the observed interference would vary[15] by more than 15°.

(2) There is no isolated s-channel resonance with unique G parity in an angular-momentum state different from the background and with an amplitude more than 45% of the background. If there were, the coherence would be partially destroyed when integrating over all angles and, more importantly, the ratio of cross sections would vary[15] by more than 20%.

(3) More strongly coupled s-channel resonances ($m = 2.1$–2.6 GeV/c^2) must exist in G-parity pairs with degenerate masses, widths, and coupling constants so that the relative phase of the two channels is constant to within 15°.

We now turn to a discussion of two-meson final states at 2.3 GeV/c. We have compared the annihilation into two neutral nonstrange mesons with a crude t-channel factorization formula. In the following, R_{ij} denotes the square of an effective matrix element for two-body production of mesons i and j, which we have equated to the observed cross section divided by the final-state

TABLE I. Cross sections versus energy.

Beam momentum (GeV/c)	$\sigma(\rho^0\pi^+\pi^-)$ (mb)	$\sigma(\omega\pi^+\pi^-)$ (mb)	Ratio	Ref.
1.26 – 1.65	2.3 ± 0.2	3.0 ± 0.2	0.77 ± 0.10	8
1.63 – 2.20	~ 1.3	~ 1.2	~ 1.1	13
2.3	0.88 ± 0.06	1.09 ± 0.07	0.81 ± 0.07	This expt.
At rest	···	···	0.8	14

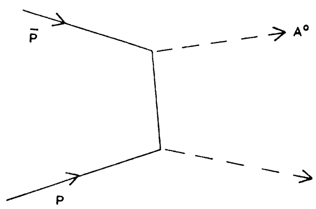

FIG. 2. t-channel process yielding a two-meson state.

center-of-mass momentum. From Fig. 2 we write

$$\frac{R_{AX}}{R_{BX}}=\frac{R_{AY}}{R_{BY}}=\frac{2R_{AA}}{R_{BA}}, \qquad (3)$$

where A, B, X, and Y are all distinct mesons. This expresses t-channel factorization with the assumption that a single trajectory is exchanged. Neglecting interference between forward and backward amplitudes[16] we obtain the second equality by noting that only one diagram exists (rather than two) if the final-state mesons are identical.

Table II lists the cross sections which we measured for eight neutral two-body final states. These were obtained from Monte Carlo fits to the 4π state and Breit-Wigner histogram fits to the 3π and 5π final states. For these states Eq. (3) gives rise to three relations,

$$\frac{R_{\rho\pi}}{R_{f\pi}}=\frac{R_{\rho\eta}}{R_{f\eta}}=\frac{R_{\rho\omega}}{R_{f\omega}}=\frac{2R_{\rho\rho}}{R_{f\rho}}.$$

From Table II we obtain, respectively,

0.57, 0.65, 0.50, and 0.50,

which are equal[17] within the uncertainties of the cross sections.

This agreement suggests not that this crude model is a quantitative one, but that $\lesssim 25\%$ of the events in any of these channels come from the decay of an s-channel resonance near 2.5 GeV/c^2 with unique isospin or G parity. This conclusion is consistent with the absence of backward peaks in the elastic and $K\bar{K}$ angular distributions at 2.3 GeV/c.[18]

TABLE II. Two-body cross sections at 2.3 GeV/c.

Final state	Final-state c.m. momentum (GeV/c)	Cross section [a] (μb)
$\omega^0\rho^0$	1.00	168 ± 35
$\omega^0 f^0$	0.73	246 ± 45
$\rho^0\rho^0$	1.02	68 ± 16
$\rho^0 f^0$	0.75	198 ± 30
$\rho^0\pi^0$	1.15	51 ± 15
$f^0\pi^0$	0.94	72 ± 19
$\rho^0\eta^0$	1.08	5 ± 2
$f^0\eta^0$	0.84	6 ± 3

[a] These refer to charged pionic decay modes only.

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[1]A. Dar *et al.*, Phys. Rev. Lett. 12, 82 (1964); K. Gottfried and J. D. Jackson, Nuovo Cimento 34, 735 (1964); H. Harari, Phys. Rev. Lett. 26, 1400 (1971).

[2]R. Dolen *et al.*, Phys. Rev. 166, 1768 (1969). Further analysis of other final states in this experiment with respect to the effects of overlapping resonances is in progress.

[3]The opposite case has been discussed by H. Nicholson *et al.*, Phys. Rev. Lett. 23, 603 (1969).

[4]The $\rho\pi\pi$ and $\omega\pi\pi$ final states consist mainly of double-resonance production; see also W. W. M. Allison *et al.*, Phys. Rev. Lett. 24, 618 (1970); and J. W. Chapman *et al.*, Nucl. Phys. B24, 445 (1970).

[5]We should emphasize that the final states treated in this paper are presumably typical ones, having been chosen mainly on the basis of experimental convenience. Of course, it is possible that the $\rho\pi\pi$ and $\omega\pi\pi$ final states are not typical, in which case all of our conclusions might not apply to a general annihilation final state. In experiments aimed at searching for cross-section enhancements as a function of energy, possible effects have been confined to a few exceptional final states: W. A. Cooper *et al.*, Phys. Rev. Lett. 20, 1059 (1968); G. Kalbfleisch *et al.*, Phys. Lett. 29B, 259 (1969); A. Benvenuti *et al.*, Phys. Rev. Lett. 27, 283 (1971).

[6]W. W. M. Allison *et al.*, Nucl. Instrum. Methods 79, 841 (1970).

[7]These will be discussed elsewhere in connection with the elastic scattering data.

[8]Allison *et al.*, Ref. 4.

[9]H. J. Behrend *et al.*, Phys. Rev. Lett. 27, 61 (1971). Their result is not entirely in agreement with previous work. However, our conclusions are insensitive to the precise value, and would be strengthened for lower values of the branching ratio.

[10]Insofar as the coherence is unity, a unique relative phase may be defined for all contributing amplitudes (see Ref. 8). In particular the same phase must apply over the whole energy range 1.26–1.65 GeV/c.

[11]The phase used here is the observed relative ρ/ω phase in the 2π decay channel, defined as φ in Eq. (8) of Ref. 8.

[12]A discussion of the statistical method is given on p. 6 of S. Flatté, Phys. Rev. D 1, 1 (1970).

[13]Chapman *et al.*, Ref. 4. Their experiment covered

the momentum range 1.6–2.2 GeV/c.

[14]L. Montanet, in *Proceedings of the Lund International Conference on Elementary Particles*, edited by G. von Dardel (Berlingska-Boktryckeriet, Lund, Sweden, 1970), p. 220. Some of the in-flight results appear unreliable, however; see p. 206.

[15]Here we assume that the width of such an isolated s-channel resonance is less than 300 MeV, the range of c.m. energy under discussion.

[16]The experimental angular distributions are in reasonable accord with this assumption. We are effectively ignoring $I=\frac{5}{2}$ exchange which is either small or forbidden for the reactions of Table II.

[17]This fit also predicts $\sigma(\pi^0\pi^0)=11\pm4$ μb. From $\sigma_{\rm expt}(\pi^+\pi^-)=45\pm3$ μb and $I=\frac{1}{2}$ exchange which seems to dominate the $\pi^+\pi^-$ distribution, we get a (semiexperimental) value of $\sigma(\pi^0\pi^0)=10\pm3$ μb for comparison.

[18]W. W. M. Allison *et al.*, to be published.

Coherent Production of $K^{*-}(890)$ by K^- at 10 and 12.7 GeV/c on $A\approx 20$ Nuclei

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Coherent $K^{*-}(890)$ production by K^- of 10.0 (12.7) GeV/c on $A\approx 20$ nuclei is observed with $\sigma_A=150\pm50$ (131 ± 35) μb/nucleus. The K^* alignment, t' distribution and cross section are consistent with production via isoscalar, natural-parity exchange.

Because exchange of isoscalar trajectories of natural parity contributes to $K^{*-}(890)$ production by K^- beams on free protons,[1] coherent production of $K^*(890)$ on complex nuclei is expected.[2] So far this coherent production has been observed only in deuterium experiments.[3] We report here evidence for coherent $K^*(890)$ production from nuclei with $A\approx 20$.

Our results are based on two bubble-chamber experiments with 10.0- and 12.7-GeV/c K^- beams.[4] The 10.0-GeV/c exposure was made in the CERN 1.2-m heavy-liquid bubble chamber filled with a a propane-freon mixture (atomic composition C:F:Br:H $\approx$ 6:3:1:13). The 12.7-GeV/c exposure was made in the Brookhaven National Laboratory 80-in. chamber filled with a neon-hydrogen mixture (Ne:H $\approx$ 12:7). The two exposures together yield roughly one event per μb of cross section.

The radiation lengths of these liquids are 26 and 44 cm, respectively. This gives a mean probability for detection of both γ's from a π^0 of about 65% for each experiment.

The film was scanned for one-prong events with no indication of nuclear breakup and with any number of V^0's or γ's pointing to the interaction. In order to eliminate spurious γ's (mainly bremsstrahlung) from our sample, cuts on angles between γ's and on γ momenta have been defined from a Monte Carlo study of multi-π^0 events. After these cuts, events belonging to the topologies 1-prong + 1V^0 and 1-prong + 2γ were fitted respectively to the reactions (4C