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Reaction $\bar{p}p \to \overline{K}K\pi\pi\pi$ at 1.6–2.2 GeV/c†

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Antiproton-proton annihilations into final states $K_1^0K_1^0\pi^+\pi^-\pi^0$, $K_1^0K^\pm\pi^\mp\pi^+\pi^-$, $K_1^0K_2^0\pi^+\pi^-m\pi^0$ ($m \geq 1$), and $K^+K^-\pi^+\pi^-\pi^0$ have been studied in a bubble-chamber experiment at six incident momenta in the range 1.6–2.2 GeV/c, corresponding to a total center-of-mass energy range 2290–2500 MeV. The explicit use of charge-conjugation symmetry allowed the study of the $K^+K^-\pi^+\pi^-\pi^0$ final state with very few ambiguities in our sample of events. A search for direct-channel resonances revealed a ~3-standard-deviation enhancement in the $K^+K^-\omega$ channel at 2350 MeV, but no corresponding enhancement appears in the $K_1^0K_1^0\omega$ or $K_1^0K_2^0\omega$ channels. No evidence was found for a previously reported $K^*K\pi\pi$ resonant state near 2360 MeV.

I. INTRODUCTION

As part of a continuing bubble-chamber study[1,2] of $\bar{p}p$ interactions in the incident momentum range 1.6–2.2 GeV/c, the following reactions have been studied:

$$\bar{p}p \to K_1^0K_1^0\pi^+\pi^-\pi^0 \quad \text{(207 events)}, \tag{1}$$

$$\bar{p}p \to K_1^0K^\pm\pi^\mp\pi^+\pi^- \quad \text{(347 events)}, \tag{2}$$

$$\bar{p}p \to K_1^0K_2^0\pi^+\pi^-m\pi^0, \quad m \geq 1 \tag{3}$$

$$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0 \quad \text{(578 events)}. \tag{4}$$

Reactions (1), (2), and (4) are the three overconstrained $\bar{p}p \to \overline{K}K\pi\pi\pi$ channels that can normally be studied in a bubble-chamber experiment. Reaction (3) includes the $K_1^0K_2^0\pi^+\pi^-\pi^0$ final state, but this final state contains two unseen particles (K_2^0 and π^0) and so cannot be distinguished in a bubble chamber from the final states $K_1^0K_2^0\pi^+\pi^-m\pi^0$, $m > 1$. Reaction (3) is included here because it does give an upper limit on the channel $K_1^0K_2^0\omega$.

A major aim of this experiment was to search for evidence of direct-channel resonances. The total center-of-mass energy range of 2290–2500 MeV includes the centers of two broad ($\Gamma \sim 150$ MeV) structures, one with $I=1$ and one with $I=0$, seen in antiproton-nucleon total-cross-section measurements,[3] which could be due to direct-channel resonances. In addition, Oh *et al.*[4] have examined $\bar{p}p$ and $\bar{p}d$ annihilations into $\overline{K}K\pi\pi\pi$ channels and report evidence for a resonant state in the $K^*K\pi\pi$ subchannel at 2360 MeV. An earlier report from this experiment,[5] listed in the Review of Particle Properties,[6] suggested a possible resonance with odd charge-conjugation quantum number in the channels $K_1^0K_1^0\pi^+\pi^-\pi^0$ and $K_1^0K_2^0$+neutrals at 2370 MeV.

In the present work, no evidence is found for a $K^*K\pi\pi$ resonant state at 2360 MeV. In addition, the suggested odd-C resonance at 2370 MeV is not confirmed. An enhancement is seen in the $K^+K^-\omega$ channel at 2350 MeV, but no corresponding enhancement is seen in the $K_1^0K_1^0\omega$ or the $K_1^0K_2^0\omega$ channel, so the interpretation of the $K^+K^-\omega$ enhancement is not clear.

The bubble-chamber exposure consisted of 150 000 pictures of antiprotons incident in the 30-inch MURA-ANL hydrogen bubble chamber. The pictures were divided approximately equally among the six incident antiproton momenta (total center-of-mass energy) 1.62 GeV/c (2294 MeV), 1.76 (2347), 1.82 (2368), 1.88 (2389), 1.94 (2410), and 2.20 (2500). At each setting the momentum spread (full width at half-maximum) was 2.4%. The beam contamination by π's and μ's was determined to be less than 1%. All 150 000 pictures were used to obtain the sample of events of reactions (1)–(3), while only one half of the pictures were used for reaction (4).

II. EXPERIMENTAL DETAILS, REACTIONS (1)–(3)

The events comprising reactions (1)–(3) came from a study of all V events. The entire film was double scanned for single-V and double-V events, disagreement scanned, measured, and processed through the pregeometry, geometry, and kinematics programs CAST, TVGP, and SQUAW. Three remeasurement passes were made. Of the roughly 5000 candidates, 15% were consistent with being a $K_1^0 \to \pi^+\pi^-$ decay, since they passed the one-constraint (1C) fit to this hypothesis, but failed to "point" to any acceptable beam-track interaction vertex – i.e., failed all 3C fits on four successive measurements. These events were examined again, with the aid of the results of the 1C fit, for possible origins previously overlooked. Less than 1% of these events had undiscovered acceptable origins. The bulk of them were understandable as a variety of background phenomena not related to the cross sections which were being measured.[2] The point to be made is that there was no unaccounted for loss of events resulting from mismeasurement, misidentification of origin, or inadequacies of the fitting program. A small loss resulting from K_1^0 scatters and undetected scatters of the decay products of the K_1^0 was calculated and found to be negligible.

All events which passed the 3C fit to a K_1^0 decay from a specific beam-track interaction were reexamined in a bubble-density scan in an attempt to remove all kinematic ambiguities.

Two-V events were accepted as reaction (1) if they fitted the $K_1^0K_1^0\pi^+\pi^-\pi^0$ hypothesis (1C at the primary vertex) with confidence level $\alpha > 10^{-4}$ (at the primary vertex) and did not fit the $K_1^0K_1^0\pi^+\pi^-$ hypothesis (4C) with $\alpha > 10^{-4}$. Only six events fitted both hypotheses, and all favored the latter one. This procedure produced a total of 207 events. An appropriate missing-mass plot showed that contamination from the $K_1^0K_1^0\pi^+\pi^-\pi^0\pi^0$ final state was $\lesssim 1\%$.

Events were accepted as reaction (2) if they fitted the $K_1^0K^\pm\pi^\mp\pi^+\pi^-$ hypothesis (4C) with $\alpha > 10^{-3}$ (at the primary vertex) and the bubble densities of the tracks were consistent with this hypothesis. The final sample of 347 events contained no events with unresolved ambiguities with respect to permutations of the tracks. Contamination from other channels was estimated to be $< 2\%$.

Reaction (3) was rather more difficult, since it was not possible to select a specific sample of events that all belonged to this reaction. Two-prong one-V events were assigned to the final state $K_1^0\pi^+\pi^-$MM, where MM (missing mass) was assumed to contain an unseen K^0 and at least one π^0, if (a) at the primary vertex there was no 4C fit with $\alpha > 10^{-3}$ or 1C fit with $\alpha > 10^{-2}$ that was consistent with the observed bubble densities; (b) the bubble densities were consistent with the $K_1^0\pi^+\pi^-$MM hypothesis; and (c) the calculated missing mass plus twice its error was greater than the combined rest mass of a K^0 and a π^0. These rules led to a total of 524 unambiguous $K_1^0\pi^+\pi^-$MM events, and 120 events ambiguous with $K_1^0K^+\pi^-m\pi^0$ or $K_1^0K^-\pi^+m\pi^0$, $m \geq 2$. The ambiguous events were then assumed to be distributed amongst these three reactions in the same ratio as the nonambiguous events (89 to the $K_1^0\pi^+\pi^-$MM channel, 31 to the other two). It was estimated that up to 2% of real $K_1^0\pi^+\pi^-$MM events may have been lost by falsely fitting the $K_1^0\pi^+\pi^-K^0$ hypothesis.

The $K_1^0\pi^+\pi^-$MM events included both $K_1^0K_2^0\pi^+\pi^-m\pi^0$ and $K_1^0K_1^0\pi^+\pi^-m\pi^0$ $(m \geq 1)$, with one unseen K_1^0 decay in the latter case. The numbers of $K_1^0K_1^0\pi^+\pi^-m\pi^0$ events with both K_1^0 decays seen, the $K_1^0\to\pi^0\pi^0$ branching ratio, and the known geometrical efficiencies were used to calculate the expected numbers of $K_1^0K_1^0\pi^+\pi^-m\pi^0$ events with one K_1^0 unseen. Then by subtraction the numbers of $K_1^0K_2^0\pi^+\pi^-m\pi^0$ events were obtained.

To obtain cross sections for reactions (1)–(3) from the numbers of events, an incident-beam-track count was made at each momentum, and an average beam pathlength determined. Correction was made for $K_1^0\to\pi^0\pi^0$ decays using a $K_1^0\to\pi^+\pi^-$ branching fraction of 0.684. Incident-momentum-dependent corrections were made for K_1^0 decays outside the bubble chamber or very close to the primary vertex, and for scanning and geometry losses, the average correction being ~1.30. These corrections were relatively independent of the mass of any particular combination of final-state particles, so any mass plots made for these three reactions are with real events (not weighted events).

The numbers of events and the cross sections for reactions (1) and (2) and the final cross sections for reaction (3) are given in Table I. All sources of error are included in the errors given in the table, including, for reaction (3), errors arising from the assignment of ambiguous events. In all cases the statistical error in the number of events dominates.

The cross section for reaction (3) gives an upper limit for the reaction

$$\bar{p}p\to K_1^0K_2^0\pi^+\pi^-\pi^0\,. \tag{5}$$

The cross sections for the contaminant final states $K_1^0K_2^0\pi^+\pi^-m\pi^0$, $m \geq 2$, might be expected to be the same order of magnitude as for $K_1^0K_1^0\pi^+\pi^-m\pi^0$, $m \geq 2$ (average 30 μb), $K_1^0K_1^0\pi^+\pi^+\pi^-\pi^-$ (average 8 μb), $K_1^0K_2^0\pi^+\pi^+\pi^-\pi^-$ (average 8 μb), which also

TABLE I. Numbers of events (N) and cross sections (σ) for reactions (1), (2), (3).

	Lab momentum (GeV/c)					
	1.62	1.76	1.82	1.88	1.94	2.20
(1) $K_1^0K_1^0\pi^+\pi^-\pi^0$						
N	23	40	47	36	25	36
σ (μb)	117	172	200	136	106	151
Error (μb)	27	31	34	26	23	29
(2) $K_1^0K^\pm\pi^\mp\pi^+\pi^-$						
N	49	65	59	67	56	51
σ (μb)	181	212	183	181	179	161
Error (μb)	27	28	25	24	25	24
(3) $K_1^0K_2^0\pi^+\pi^-m\pi^0$ $(m \geq 1)$						
σ (μb)	237	176	168	229	192	156
Error (μb)	39	39	39	34	33	36

have four or more pions.[2] If this were the case, then most of the cross section for reaction (3) is really reaction (5).

III. EXPERIMENTAL DETAILS, REACTION (4)

To obtain the sample of $\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$ events, approximately 50 000 four-prong events were measured. About 8500 events fit the 1C hypothesis $\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$ with a confidence level >1%, but all of these could also be multipion annihilations, many could have a missing neutral kaon, and there were very often ambiguities with respect to permutations of the tracks. To sort out real $K^+K^-\pi^+\pi^-\pi^0$ events, it was necessary to use bubble-density information.

To remove $K^+K^-\pi^+\pi^-\pi^0$ fits that would be difficult or impossible to resolve from multipion annihilations with any degree of certainty using bubble densities, the following rules were imposed before arriving at our final sample of events: (a) Each outgoing track must be longer than 7 cm, except that a kaon of less than 200 MeV/c must be at least 3 cm long; (b) at least one kaon track must have momentum less than 595 MeV/c, corresponding to a relative K to π ionization ratio $I > 1.60$ (an exception to this rule is mentioned below); (c) at least one kaon that passes rule (b) must have dip angle less than 57.3°, or less than 68.8° if its momentum is below 453 MeV/c ($I > 2.0$).

Scanners examined all candidates at the scanning table. The scanners were given, for each track on each view, the expected projected bubble density (relative to a minimum ionizing track) for the multipion hypothesis and for the $K^+K^-\pi^+\pi^-\pi^0$ fits. A decision on a track was made only if the ratio I was greater than 1.60 and the dip angle satisfied rule (c) above. A $K^+K^-\pi^+\pi^-\pi^0$ fit was accepted if it passed rules (a)–(c) above and a favorable decision was made on all tracks on which a decision was required. Possible $K^\pm\pi^\mp\pi^+\pi^-K^0$ contamination is discussed later. For a few events where the decision on a track was not clear, and for all the exceptions to rule (b), the numbers of bubbles on all tracks were counted, a bubble-density χ^2 was calculated for each hypothesis, and if the χ^2 probability was less than 6%, the hypothesis was rejected.

Some events were not unambiguously resolved even after careful bubble counting. Nine events remained ambiguous between two $K^+K^-\pi^+\pi^-\pi^0$ permutations, and each of the latter was given a weight of 0.5. Thirty-one events remained ambiguous between $K^+K^-\pi^+\pi^-\pi^0$ and multipion annihilations, and were given weights of 0.5 [27 of the 31 were those for which rule (b) was laid aside]. The distribution of these 31 events was 0, 1, 0, 10, 6, and 14, respectively, for the six momenta (lowest to highest).

The bubble-density scanners could make errors in two ways: They could exclude good $K^+K^-\pi^+\pi^-\pi^0$ events, or include events of some other reaction. The second of these was corrected by a physicist examining all the potential $K^+K^-\pi^+\pi^-\pi^0$ events found by the scanners and removing all background events. Two measures of the size of the first error were obtained:

(a) Events fitting the 4C hypothesis $\bar{p}p \to K^+K^-\pi^+\pi^-$ were included in the bubble-density scan. Most of these events really belonged to this hypothesis. Those excluded by the scanners were checked and if necessary rechecked in order to get the correct assignment. Then the error rate for these events was determined and was assumed to be the same as for $K^+K^-\pi^+\pi^-\pi^0$ events. This error-rate determination used only $K^+K^-\pi^+\pi^-$ events that passed the rules (a)–(c) above.

(b) A sample of 700 of the original 8500 candidates was reexamined by a physicist (specifically those with a $K^+K^-\pi^+\pi^-\pi^0$ fit that had $\chi^2 < 0.8$ and three-pion mass in the ω region). The statistics here were not as good as in (a).

Combining the results of (a) and (b) gave correction factors of 1.10, 1.07, 1.06, 1.12, 1.01, 1.06, respectively, for the six momenta (lowest to highest). It is not unreasonable to have some momentum dependence in these factors, which results from changes in general track quality and nonrandom distribution of the bubble-density scanners among the different momenta. Hence each event [except those involved in method (b) above] was given a weight equal to the correction factor for that momentum. Cross sections were given an additional ±3% error because of uncertainty in these correction factors.

Correction for $K^+K^-\pi^+\pi^-\pi^0$ events that were lost because they did not pass rules (a)–(c) above was made by giving appropriate weights to the $K^+K^-\pi^+\pi^-\pi^0$ events in the sample, as explained in the following paragraphs.

The loss through rule (c) was corrected by a weight obtained by rotating each event about the incident beam direction and calculating the fraction of the time that the event passed this rule. This weight was often 1.0, and at most 1.57 when the one slow ($I > 1.60$) kaon was perpendicular to the beam track.

Explicit use of charge-conjugation symmetry gave the corrections for rule (b). The charge conjugate of each event was transformed to the rest frame of its proton. Each event was given a weight of 1.0 or 2.0 according to whether its charge conjugate would or would not have passed this rule. Rule (b) was laid aside if a $K^+K^-\pi^+\pi^-\pi^0$ fit and its charge conjugate both failed the rule, and then the fit was considered in the bubble-density scan if its lower kaon momentum was less than that of the charge conjugate. [This is the exception to rule (b) mentioned earlier.] If the event was then assigned to this fit it was given a weight of 2.0. The number of events that made this exception and had to be bubble-density scanned varied from 8 at the lowest incident momentum to 35 at the highest for a total of 122 events. The weight discussed in this paragraph is referred to later as the charge-conjugate weight.

To correct for events lost by rule (a), each event was given a weight according to the probability that the outgoing tracks would have decayed or interacted less than 7 cm (or 3 cm) from the event origin. This weight ranged in value from 1.06 to 1.15. In addition, if an event and its charge conjugate passed rule (b), but the latter had a pion momentum less than 63 MeV/c or a kaon momentum less than 120 MeV/c (which correspond to ranges in hydrogen of 7 cm and 3 cm, respectively), a weight of 2.0 was given. A further momentum-independent 1% correction was made to account for events that did not pass rule (b) and whose charge conjugates had very slow pions or kaons.

Events of the reaction $\bar{p}p \to K^+\pi^-\pi^+\pi^-\bar{K}^0 m\pi^0$, $m \geq 0$, often fitted the $K^+K^-\pi^+\pi^-\pi^0$ hypothesis, and those such events with a slow ($I > 1.60$) K^+ and a fast ($I < 1.60$) pseudo-K^- (or a very dipped pseudo-K^-) would have been included in the $K^+K^-\pi^+\pi^-\pi^0$ sample (and similarly for the charge-conjugate reaction). In the physicist check of the $K^+K^-\pi^+\pi^-$-π^0 sample, events that were kinematically consistent with this contaminant reaction and that had (pseudo) $K^\pm$ with ionization ratio I in the range 1.50–1.60 were examined carefully and a decision was made on the track. The remaining contamination (or, in general, any such contamination) can be determined from a study of four-prong events with visible K_1^0 decays. In the present experiment this was made easier because four-prong events had been measured irrespective of any associated V. Of 260 real K_1^0 events so measured, 12 would have been accepted into the final $K^+K^-\pi^+\pi^-\pi^0$ sample had the K_1^0 been unobserved. A contamination by events with unseen K_1^0 or K_2^0 decays, of 30 ± 10 μb, at each momentum, was thus deduced.

The final sample of $K^+K^-\pi^+\pi^-\pi^0$ events contained 578 events (including the 31 events ambiguous with multipion annihilations), each with a weight equal to the product of all the contributing weights mentioned above. This weight ranged from 0.33 to 3.7, with the large majority clustered around 1.1 or 2.2. Weights less than 1 occur only for the ambiguous events. The average weight was 1.49, and did not vary significantly between the different incident momenta. 167 events had a charge-conjugate weight of 2.0; thus without charge-conjugation symmetry it would have been necessary to find, or somehow correct for, approximately 160 additional events with both kaons fast (momentum > 595 MeV/c, $I < 1.60$).

To get the cross section at each incident momentum, the ratio of weighted events to well-measured four-prong events in the fiducial volume was multiplied by the total four-prong cross section. The total four-prong cross sections were determined by counting the numbers of four-prong events and beam tracks in a given fiducial volume on 2200 pictures at each momentum, and have 2.7% statistical errors.

Two further corrections to the cross sections were considered. These were the effect of the 1%-confidence-level cut on the kinematic fits and contamination by $K^+K^-\pi^+\pi^-\pi^0\pi^0$ events. These opposing effects were both estimated to be approximately 3%, independent of incident momentum.

The raw number of events, the weighted number of events, the four-prong cross section, and the final $K^+K^-\pi^+\pi^-\pi^0$ cross section at each incident momentum are given in Table II. The error quoted includes the statistical error, an error on the neutral-kaon contamination (± 10 μb), an error on the bubble-density-scan correction factor (±3%), an error due to possible misassignment of ambiguous events, and the statistical error on the four-prong cross section (±2.7%). The statistical error dominates.

TABLE II. Numbers of events and cross sections (σ) for reaction (4).

	Lab momentum (GeV/c)					
	1.62	1.76	1.82	1.88	1.94	2.20
Unweighted events	65	117	82	104	118	92
Weighted events	91	188	120	157	174	137
σ(4-prong) (mb)	29.8	27.3	27.2	25.8	25.5	23.0
$\sigma(K^+K^-\pi^+\pi^-\pi^0)$ (μb)	410	681	452	533	590	503
Error (μb)	59	76	59	68	64	71

We believe that our method of obtaining the $K^+K^-\pi^+\pi^-\pi^0$ event sample, with the high degree of resolvability of kaons from pions used in the bubble-density scan (relative K to π ionization ratio greater than 1.60, except for a few events) in a bubble chamber with good optics, and the use of charge-conjugation symmetry, has made the event sample essentially free of multipion contamination and (when weighted) practically without bias with respect to any particular region of phase space. We assume that CP invariance is good.[7,8]

In the remainder of this paper, weighted $K^+K^-\pi^+\pi^-\pi^0$ events are always used unless stated otherwise.

IV. CROSS SECTIONS

The cross sections for the four reactions are plotted in Fig. 1 as a function of center-of-mass energy. The horizontal error bars come from the ±1.2% spread on the incident beam momenta. Also shown are measurements at 1.2-GeV/c (Refs. 9 and 10) and 2.7-GeV/c (Ref. 11) incident momenta. The sum of the cross sections for reactions (1), (2), and (4) given by Oh *et al.*[4] are in good agreement with our values of this sum at the three momenta (1.62, 1.82, and 1.94 GeV/c) where the data can be compared.

There is an apparent enhancement at 2347 MeV in the reaction $\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$. The data point at 2347 MeV lies nearly 3 standard deviations above the average of the other five points.[12] This enhancement can be attributed mainly to the $K^+K^-\omega$ channel, which is discussed below.

V. $\bar{p}p \to \bar{K}K\omega$

The $\pi^+\pi^-\pi^0$ mass spectra for reactions (1) and (4) show clear evidence for ω production. These mass spectra are shown in Fig. 2, for all incident momenta combined. The narrower ω peak in Fig. 2(b) results from the better mass resolution of reaction (1). Figure 3(a) shows the cross section for $K^+K^-\pi^+\pi^-\pi^0$ with $\pi^+\pi^-\pi^0$ mass in the range 744–824 MeV, and Fig. 3(b) shows the cross section for $K_1^0K_1^0\pi^+\pi^-\pi^0$ with $\pi^+\pi^-\pi^0$ mass in the range 764–804 MeV, as a function of the center-of-mass energy. A fit of the mass interval 664–904 MeV of Fig. 2(a) to a Gaussian-shaped resonance plus a linear background gave a resonance mass of 787 MeV and a full width at half-maximum of 43 MeV, and implied that 97% of the resonance lay within the mass interval 744–824 MeV while 23% of the events in this mass interval are background (i.e., non-ω) events. The numbers of events in Fig. 2(b) are too small to do a similar fit there, but from

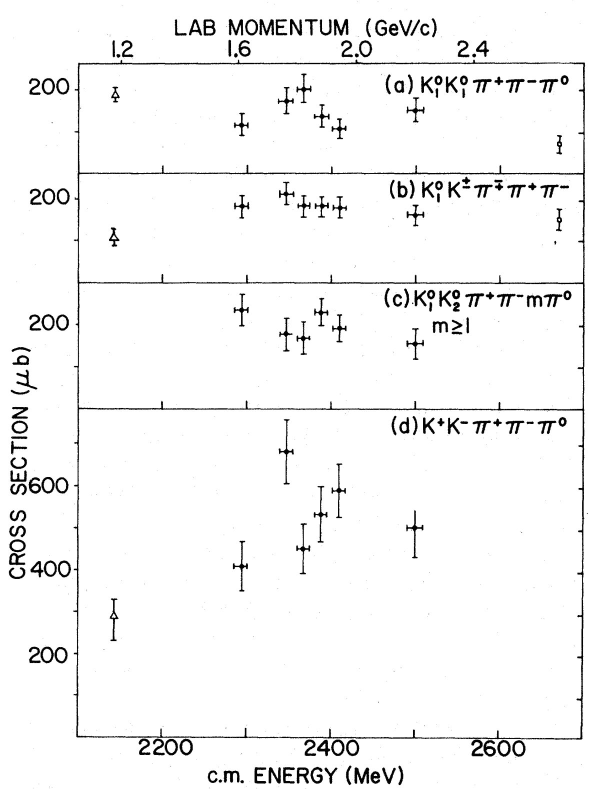

FIG. 1. Cross sections for reactions (1)–(4). The open triangles are from Refs. 9 and 10, the open squares from Ref. 11.

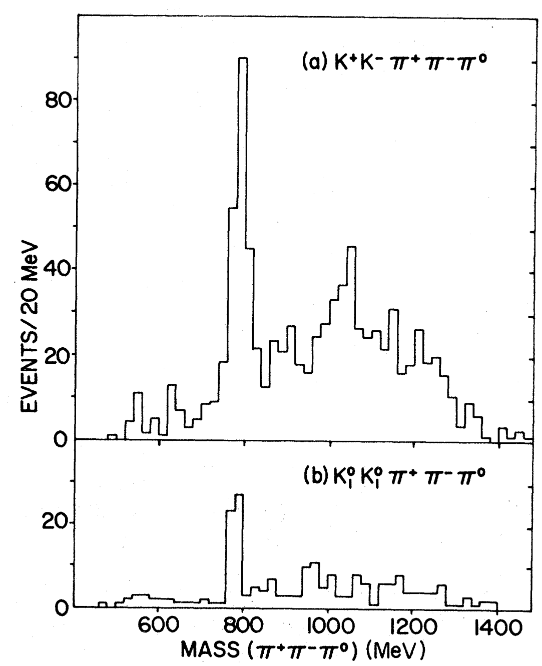

FIG. 2. The three-pion mass spectra of (a) reaction (4), (b) reaction (1), with all incident momenta combined.

the histogram it was estimated that the center of the resonance was at 781 MeV, and the 764–804-MeV mass interval contained ~10% non-ω events.

There is a suggestion of a peak at 2368 MeV in Fig. 3(b) (as noted earlier[5]), but by itself it is not statistically significant. There is a strong enhancement at 2347 MeV in Fig. 3(a). Various estimates of the statistical significance of the latter enhancement can be made. If a straight line of zero slope is fitted to the five lower-energy points of Fig. 3(a), a χ^2 probability of 0.2% is obtained, with the 2347-MeV point contributing 9.4 of the total χ^2 value of 16.9 (we scaled appropriately the errors on the measured points to get the expected errors on the fitted points). A straight line of nonzero slope does not improve this χ^2. If the 2347-MeV point is omitted, a fit to the remaining four lower-energy points gives a χ^2 value of 1.5, a change of 15.4. The weighted average and error in the average of these latter four points is 104 ± 15 μb compared with the 250 ± 47 μb at 2347 MeV, a difference of 146 ± 49 μb. We conclude that the significance of the enhancement is 3 to 4 standard deviations (SD).

One interpretation of such an enhancement would be in terms of a direct-channel resonance. However, a resonance should decay equally into $K^+K^-\omega$ and $K^0\overline{K}{}^0\omega$ (assuming that isospin is conserved), and the latter would appear as either $K_1^0K_2^0\omega$ or $K_1^0K_1^0\omega + K_2^0K_2^0\omega$, depending on whether the resonance had even or odd charge-conjugation quantum number C. Neither Fig. 3(b) nor Fig. 1(c) (which includes the $K_1^0K_2^0\omega$ channel) shows an enhancement at 2347 MeV. If C were odd, an enhancement of 73 ± 25 μb would be expected in Fig. 3(b), compared to the observed 4 μb, a discrepancy of 2.7 SD. If C were even, a (146 ± 49)-μb enhancement would be expected in Fig. 1(c), compared with an observed -30 μb, a 3.5-SD discrepancy. (It is assumed in both cases that the background level is given by the average of the same four nearer points.)

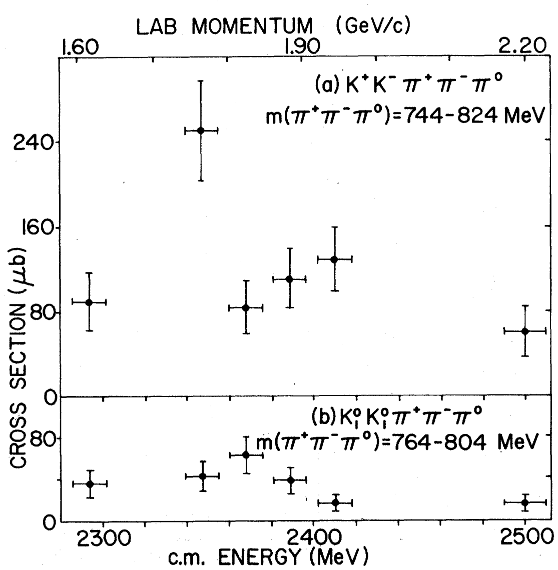

FIG. 3. The cross sections for (a) reaction (4) with three-pion mass in the interval 744–824 MeV, and (b) reaction (1) with three-pion mass in the interval 764–804 MeV.

Thus, the simplest conclusion appears to be that there is a statistical fluctuation in Fig. 3(a) – or in Fig. 1(c) or Fig. 3(b) (there are a relatively large number of $\bar{p}p$ channels in which to look for such a fluctuation). Otherwise, there could be two overlapping resonances coupled to $K\overline{K}\omega$, or the background level in Fig. 1(c) or Fig. 3(b) could have been seriously overestimated. Two overlapping resonances could produce an enhancement in $K^+K^-\omega$ but not in $K^0\overline{K}{}^0\omega$ if they had different isospin but the same quantum numbers J, P, and C, and the same internal orbital angular momenta – an *a priori* rather unlikely situation. The background level in Fig. 3(b) could have been overestimated, for example, if there was another resonance at ~2375 MeV.

An examination of various angular distributions in the $K^+K^-\omega$ system and of K^+K^- and $K^\pm\omega$ mass plots revealed no striking differences between the 2347-MeV events and those at other energies, within the limited statistics.

The points in Fig. 3 include some non-ω background. Background-subtracted $K\overline{K}\omega$ cross sections were derived by assuming that the background level varies linearly with $\pi^+\pi^-\pi^0$ mass in the mass interval 664–904 MeV (or 724–844 MeV for $K_1^0K_1^0\pi^+\pi^-\pi^0$) and that essentially all ω events lie in the 744–824-MeV (764–804-MeV) mass band. Three-pion mass plots from Monte Carlo generated $KK\pi\pi\pi$ and $K^*K\pi\pi$ events showed that the assumed linearity is good to within ~3% for phase-space-like events. The resulting cross sections are given in Table III. The background-subtracted $K^+K^-\omega$ cross sections give somewhat smaller estimates of the significance of the 2347-MeV enhancement, compared to the earlier estimates. This is due equally to the increased errors (from statistical errors on the background events outside the ω bands) and to the fact that the background level is slightly higher at 2347 MeV. This latter effect could be partly offset by taking a slightly wider ω band.

Other published values for $K\overline{K}\omega$ cross sections at nearby energies are 82 ± 5 μb ($K_1^0K_1^0\omega$) and 94 ± 17 μb ($K^+K^-\omega$) at[9,10] 1.2 GeV/c (2142 MeV) and 4 ± 4 μb ($K_1^0K_1^0\omega$) at[11] 2.7 GeV/c (2670 MeV).

The $\pi^+\pi^-\pi^0$ mass spectrum for the events of reaction (4) at 2347 MeV is shown in Fig. 4.

TABLE III. Cross sections (σ) for $K^+K^-\omega$ and $K_1^0K_1^0\omega$, $\omega \to \pi^+\pi^-\pi^0$ (after background subtractions).

	c.m. energy (MeV)					
	2294	2347	2368	2389	2410	2500
$\sigma(K^+K^-\omega)$ (μb)	71	207	67	87	112	55
Error (μb)	33	51	30	31	34	25
$\sigma(K_1^0K_1^0\omega)$ (μb)	34	41	57	33	15	12
Error (μb)	15	14	18	13	9	9

VI. $K^*(890)$ PRODUCTION

Reactions (1), (2), and (4) show clear evidence of $K^*(890)$ production. Figure 5 shows the $K\pi$ mass spectrum (excluding combinations with known $I_z = \frac{3}{2}$) for each of these three reactions with all incident momenta combined. Figure 6 shows the $K\pi$ mass spectrum at each incident momentum for the three reactions combined, with events of reactions (1) and (4) weighted by the sensitivities (μb/event) relative to reaction (2). This weight is ~1.36 for reaction (1) and ~1.16 for reaction (4).

The total number of K^*'s, N_{K^*}, and thus the quantity $S_1 = \sigma(K^*K\pi\pi) + 2\sigma(K^*K^*\pi)$, was determined for each reaction at each incident momentum. In principle, the $K\pi$ mass spectrum could be fitted to a sum of K^* Breit-Wigner amplitude and phase space, taking all reflections into account. In fact, an explicit fit is not necessary. A study of Monte Carlo generated $KK\pi\pi\pi$, $K^*K\pi\pi$, and $K^*K^*\pi$ events at these incident momenta showed that the probability P that a $K\pi$ combination have a mass in the range 840–940 MeV is 80% if the combination is a K^* and that the probability, Q, is approximately 22% if the combination is not a K^*. This value of Q is nearly independent of whether there are 0, 1, or 2 K^*'s present or whether one particle of a K^* is in the $K\pi$ combination.

For each event, there are M combinations of $K\pi$ with $I_z = \frac{1}{2}$; M is 4 for reactions (2) and (4) and 6 for reaction (1). Then the number of $K\pi$ combinations with mass in the range 840–940 MeV, N_{in}, is given by

$$N_{\text{in}} = PN_{K^*} + Q(MN - N_{K^*}),$$

where N is the number of events. The resulting formulas for N_{K^*} are

$$N_{K^*} = (N_{\text{in}} - 0.88N)/0.58 \quad [\text{reactions (2), (4)}],$$

$$N_{K^*} = (N_{\text{in}} - 1.32N)/0.58 \quad [\text{reaction (1)}].$$

Slightly improved formulas for N_{K^*} can be derived if a small incident-momentum dependence, $K\bar{K}\omega$ reflections, and small differences between K^* and non-K^* events are taken into account. The improved formulas were used to calculate S_1 for our events, but the difference from the results obtained with the simple formulas above was always less than one half of the statistical error.

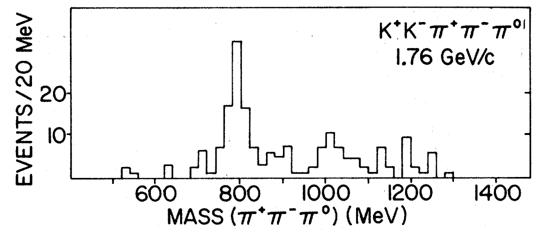

FIG. 4. The three-pion mass spectrum of reaction (4) at 1.76-GeV/c incident momentum.

The advantage in using such formulas for N_{K^*} is that the statistical error can be straightforwardly calculated. N_{in} and N can be written in terms of m_i, $i = 0$–4 (or 6), the number of events with i $K\pi$ mass combinations in the 840–940-MeV interval. Then N_{K^*} can be written in terms of the m_i, which are statistically independent.

The results for S_1, and its error, for the three reactions and their sum, are given in Table IV and plotted in Fig. 7. The result is entirely consistent with a constant, energy-independent cross section. The average fraction of K^*'s per event is 0.9 for reactions (1) and (2), 0.5 for reaction (4). The measurements of Oh *et al.*[4,13] which are also shown in Fig. 7(d), and any evidence for a direct-channel

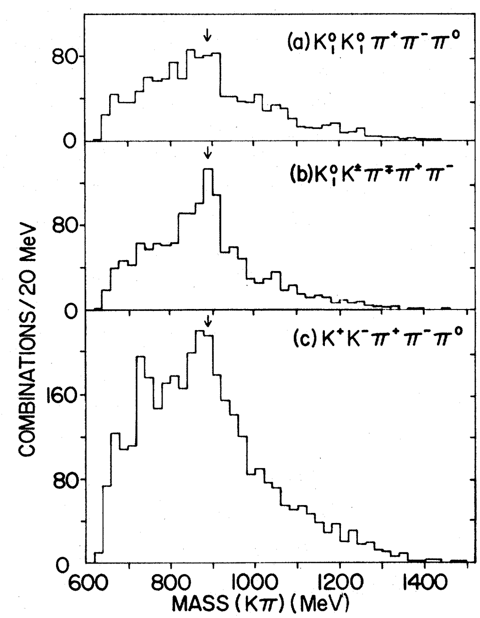

FIG. 5. The $K\pi$ mass spectra (excluding known $I_z = \frac{3}{2}$ combinations), with all incident momenta combined, for (a) reaction (1) (6 combinations per event), (b) reaction (2) (4 combinations per event), and (c) reaction (4) (4 combinations per event).

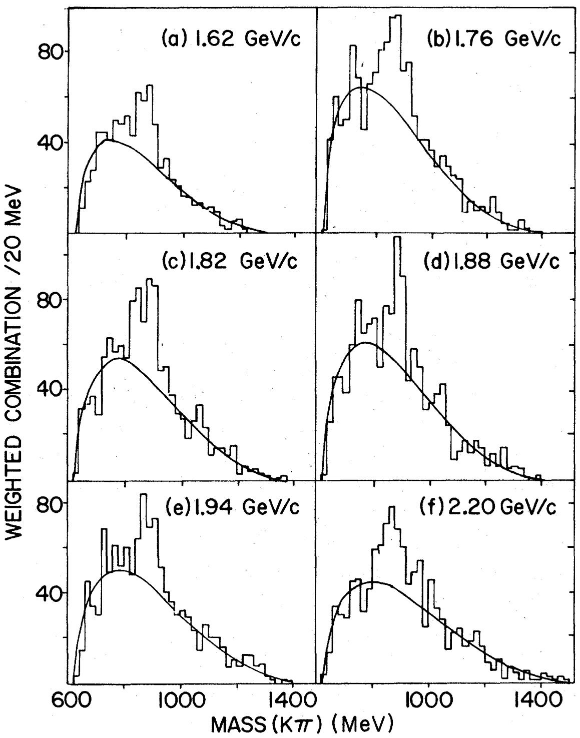

FIG. 6. The $K\pi$ spectrum (excluding known $I_z=\frac{3}{2}$ combinations) at each incident momentum with weighted events for the sum of reactions (1), (2), and (4) (see text). The solid curves show the non-K^* part of the spectra implied by the calculated K^* fractions.

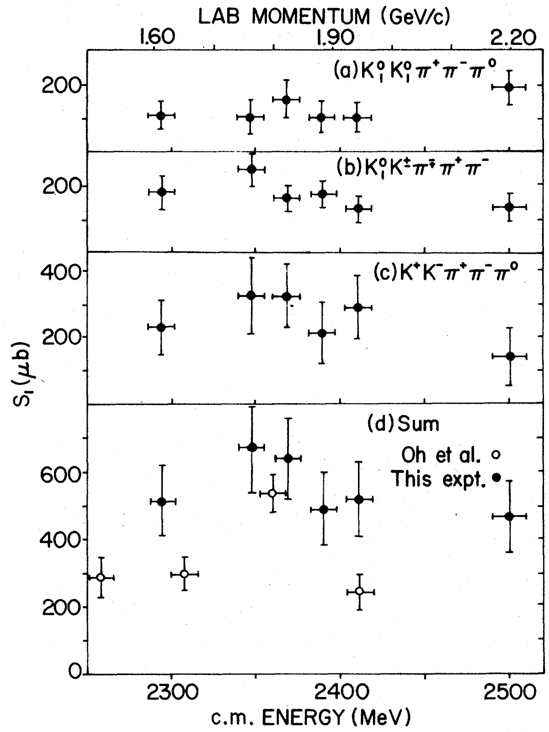

FIG. 7. The quantity $S_1=\sigma(K^*K\pi\pi)+2\sigma(K^*K^*\pi)$ for reactions (1), (2), and (4) and their sum. The open circles in (d) are the results of Oh *et al.*, recalculated as described in the text (Ref. 13).

resonance, are discussed in the next section. The K^* fractions found at 1.2 GeV/c were[9,10] 0.4, 0.65, and 0.4 for reactions (1), (2), and (4), respectively, while at 2.7 GeV/c values of 0.4 and 0.75 were found[11] for reactions (1) and (2).

Separate plots (not shown) of charged and neutral $K\pi$ mass combinations indicate that there is more charged K^* than neutral K^* in reactions (1) (momentum averaged $K^{*\mp}:K^{*0}$ ratio $r=4:1$) and (2) ($r=1.3:1$), less in reaction (4) ($r=0.5:1$). Two internal consistency checks can be made. The $\bar{p}p\to K^{*\pm}K^{\mp}\pi^+\pi^-$ cross sections measured separately in reactions (2) and (4), assuming K^* decay ratios appropriate for an $I=\frac{1}{2}$ state, should be equal. And that part of the $\bar{p}p\to K^{*0}K_1^0\pi^+\pi^-$ cross section which appears in reaction (2) should be greater than twice the $\bar{p}p\to K^{*0}K_1^0\pi^+\pi^-$ cross section appearing in re-

TABLE IV. The quantity $S_1=\sigma(K^*K\pi\pi)+2\sigma(K^*K^*\pi)$ as measured in three subchannels (see text).

	c.m. energy (MeV)					
	2294	2347	2368	2389	2410	2500
(1) $K_1^0K_1^0\pi^+\pi^-\pi^0$ (μb)	109	103	156	105	102	190
Error (μb)	44	52	58	47	45	50
(2) $K_1^0K^\pm\pi^\mp\pi^+\pi^-$ (μb)	179	249	160	174	129	135
Error (μb)	51	54	42	41	42	37
(4) $K^+K^-\pi^+\pi^-\pi^0$ (μb)	230	323	322	212	287	139
Error (μb)	83	112	95	89	94	85
Sum (μb)	518	675	638	491	518	464
Error (μb)	106	133	119	109	111	107

action (1). Both these conditions are satisfied by the data.

A simple analysis was made of scatter plots of opposite pairs of $K\pi$ masses to estimate the amount of double K^* production. Combining all incident momenta together (to get reasonable statistics), it was found that the $K^* K^*\pi$ channel contributes <20 μb (1 standard deviation) to reaction (1), 30 ± 12 μb to reaction (2), and 35 ± 30 μb to reaction (4). We conclude that double K^* production constitutes less than 40% of the value of S_1.

VII. POSSIBLE $K^*K\pi\pi$ DIRECT-CHANNEL RESONANCE

Oh *et al.*[4] have reported an enhancement in the $\bar{p}p \to K^*K\pi\pi$ cross section at 1.80 GeV/c incident momentum (2360-MeV energy). A close reading of their paper shows that the enhancement displayed is in fact in the quantity S_1 as defined above. An enhancement in S_1 is still of importance; it is a secondary – and more difficult – problem to determine whether it is in the single-K^* or the double-K^* channel, or both. They have studied the same reactions (1), (2), and (4). Their method of combining these three reactions to get the fraction of K^*'s can be questioned, because the sensitivities (μb/event) are different.[14] However, when S_1 is determined for each reaction separately and then added, the enhancement persists.[13] Their values for S_1 (from this latter method) are plotted in Fig. 7(d).

Figure 7(d) shows disagreement between the two experiments in the values of S_1, particularly at 2410 MeV, and in the size of the errors. The sensitivity (μb/event) for each reaction at each incident momentum was approximately the same for the two experiments, but the size of the errors differs by a factor of 2. The errors of Oh *et al.* are a combination of the errors on the total $K\bar{K}3\pi$ cross sections and the errors in the fractions of K^*'s; the latter are based on the square root of the numbers of background combinations in the K^* mass band.[13] The same procedure for our data gives errors approximately one half of those derived by our method described earlier. Thus we believe that Oh *et al.* may have underestimated their errors by about a factor of 2. If this is the case, their 2360-MeV point lies only 2.5 SD above a straight line drawn through their other 3 points. Figure 7(d) shows that there is no significant enhancement in S_1 near 2360 MeV in our data, nor would there be if our errors were halved.

Lastly, it should be noted that the difference in the energy dependence of S_1 between the two experiments follows from the difference in the nearly raw data of the two experiments. A comparison of Figs. 6(a), 6(c), and 6(e) of this paper with the analogous figures from the paper of Oh *et al.* [Figs. 2(b), 2(c), and 2(d)] shows that there is no noticeable change in the size of the K^* signal as the momentum changes in our experiment, whereas the K^* signal is noticeably larger at 1.80 GeV/c than at other momenta in the experiment of Oh *et al.* This enhancement apparently persists when they redraw their Fig. 2 using weighted sums of the three reactions (as we have done). We cannot think of any way that the different event-resolution techniques of the two experiments would enhance (or suppress an enhancement in) the K^* signal at one momentum and not at others. However, if our error analysis is correct, the difference in the behavior of S_1 in the two experiments is not very significant statistically.

VIII. OTHER RESONANCES

We have dealt above with the production of ω and K^*, the two major resonances seen in this experiment. We mention here other resonances also seen in the reactions (1)–(4).

There is clear evidence for ρ in the $\pi^+\pi^-$ mass spectrum of reaction (2). Using a hand-drawn background curve, it was estimated that approximately 50% of reaction (2) proceeds via ρ production. It was similarly estimated that 8% of reaction (4) proceeds via ϕ production, with $\phi \to K^+K^-$. Neither the ρ nor the ϕ cross section was found to vary strongly with incident momentum. In comparison, fits to reaction (2) gave 26% ρ production at[9] 1.2 GeV/c, 40% ρ production at[11] 2.7 GeV/c, and fits to reaction (4) gave 22% ϕ production at[10] 1.2 GeV/c.

There is also some evidence for $A_2 \to K\bar{K}$ in reactions (1), (2), and (4) (all ~4%), for $\rho \to \pi\pi$ in reactions (1) and (4), and for $D^0 \to K\bar{K}\pi$ (~3%) in reactions (2) and (4).

IX. CONCLUSIONS

Our main conclusions concern the possible presence of direct-channel resonances in the $\bar{p}p \to \bar{K}K\pi\pi\pi$ reactions. We see an enhancement in the $K^+K^-\omega$ channel at 2347 MeV, but the apparent absence of a $K^0\bar{K}^0\omega$ effect precludes an interpretation in terms of a simple direct-channel resonance. A previously suggested enhancement in the combined channels $K_1^0K_1^0\pi^+\pi^-\pi^0$ and $K_1^0K_2^0+$ neutrals at 2370 MeV is not confirmed by our $K^+K^-\pi^+\pi^-\pi^0$ cross sections. We see no evidence for the $K^*K\pi\pi$ resonance at 2360 MeV seen by Oh *et al.*[4]

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[12]The data of Oh *et al.* (Ref. 4) do not include the energy band 2340–2354 MeV in which this enhancement occurs, so no comparison can be made. Their nearest data "point," 2351–2371 MeV, overlaps the region of interest only negligibly.

[13]G. A. Smith (private communication).

[14]To obtain the equivalent of our Fig. 6, Oh *et al.* added the histograms for the three reactions without weighting by the sensitivity (μb/event). However, their sensitivity for reaction (4) appears to be considerably smaller at 1.80 GeV/c than at other momenta. Thus a difference in the fraction of K^*'s per event between the three reactions could have induced an apparent (but spurious) momentum dependence in the K^* cross section.