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$\bar{p}p$ Annihilations into $\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-$ + Neutrals near Center-of-Mass Energy 2200 MeV

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The two-prong annihilation channels for the $\bar{p}p$ interaction at four center-of-mass energies between 2150 and 2240 MeV are described. The angular distributions in the dipion annihilations are in detail different from those obtained in a previous experiment. Resonance contributions in final states involving one or more neutrals are estimated. No evidence of formation of the $T(2195)$ meson is observed.

INTRODUCTION

We report a study of two-prong annihilation channels of the $\bar{p}p$ interaction in the c.m. energy range 2150 to 2240 MeV. This range approximately covers the width of the isospin-one structure seen in the $\bar{N}N$ total cross section at 2190 MeV (Ref. 1) and is centered on the T meson observed in the CERN missing-mass experiment.[2] The data were taken at the CERN 2-m bubble chamber with four antiproton momentum settings centered at 1.23, 1.30, 1.36, and 1.43 GeV/c. Using the RHEL HPD measuring system, a total of 75 000 two-prong events were measured, of which about half are annihilations. Analysis was made using the RHEL chain of programs. The nonannihilation channels have been reported in previous articles[3] which contain details of the scanning and measuring.

$\bar{p}p \to \pi^+\pi^-$ AND $\bar{p}p \to K^+K^-$

Events of the types

$$\bar{p}p \to \pi^+ + \pi^- , \qquad (1)$$

$$\bar{p}p \to K^+ + K^- \qquad (2)$$

have been isolated; the fitting of these events is highly constrained and unambiguous. Nevertheless, all candidates were examined at the scan table by a physicist. A compilation of the cross sections for these reactions is shown in Figs. 1 and 2. The cross sections fall rapidly with beam momentum and show no obvious structure in the T-meson region. The c.m. angular distributions are shown in Fig. 3. Data on reaction (1) obtained by a Liverpool-Padua collaboration[4] are included in the diagram. We have obtained by the method of moments the coefficients of the Legendre polynomials for the distribution of reaction (1),

$$\frac{d\sigma}{d\Omega} = \sum_{l=0}^{L} a_l P_l(\cos\theta_{\mathrm{c.m.}}).$$

The a_l/a_0 so derived are given in Table I. There is no significant structure in the angular distributions which could be attributed to the narrow T meson. Nicholson *et al.*[5] have previously published the even coefficients for reaction (1) between 0.7 and 2.4 GeV/c from a counter experiment which

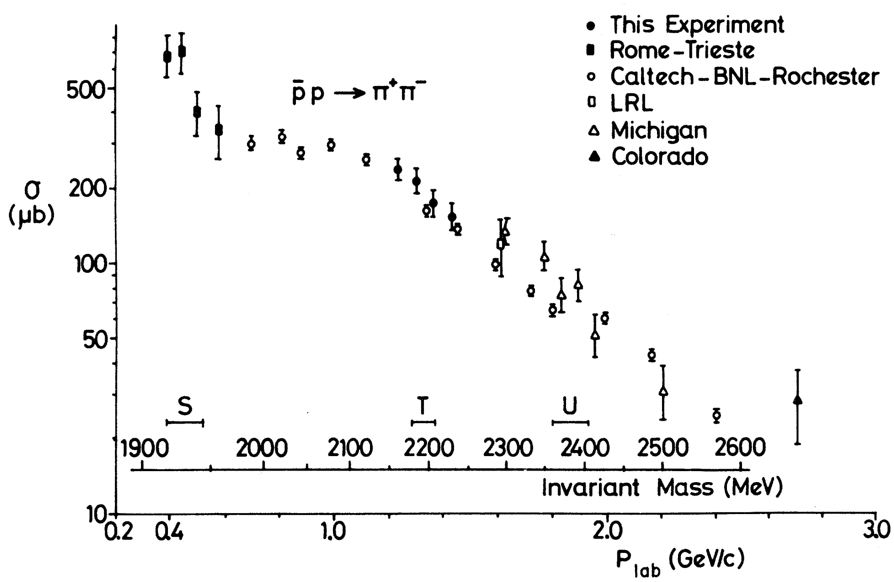

FIG. 1. Cross section vs $P_{\rm lab}$ for the reaction $\bar{p}p \rightarrow \pi^+\pi^-$. The regions of invariant mass of the S, T, and U mesons[2] are indicated.

yielded folded angular distributions. They fitted those coefficients reasonably well with $J=3$ and $J=5$ states at 2120 and 2290 MeV with widths of, respectively, 249 and 165 MeV. In the region of overlap between that and the present experiment the a_4/a_0 and a_6/a_0 ratios are in reasonable agreement, but the a_2/a_0 of Ref. 5 are somewhat higher than those we obtained. Our low-order odd coefficients are nonzero, though the over-all asymmetry of the angular distributions, defined as $2(F-B)/(F+B)$ is 0.0 ± 0.11. It is clear from Fig. 3 that the forward and backward hemispheres have very different distributions. The statistical significance of these data does not permit a detailed direct-channel analysis.

The asymmetry of the $K\bar{K}$ angular distribution averaged over the four-momenta is $2(F-B)/(F+B) = -0.35 \pm 0.22$.

$\bar{p}p \rightarrow \pi^+\pi^-\pi^0$

A total of 4692 events fit the reaction

$$\bar{p}p \rightarrow \pi^+ + \pi^- + \pi^0\ , \tag{3}$$

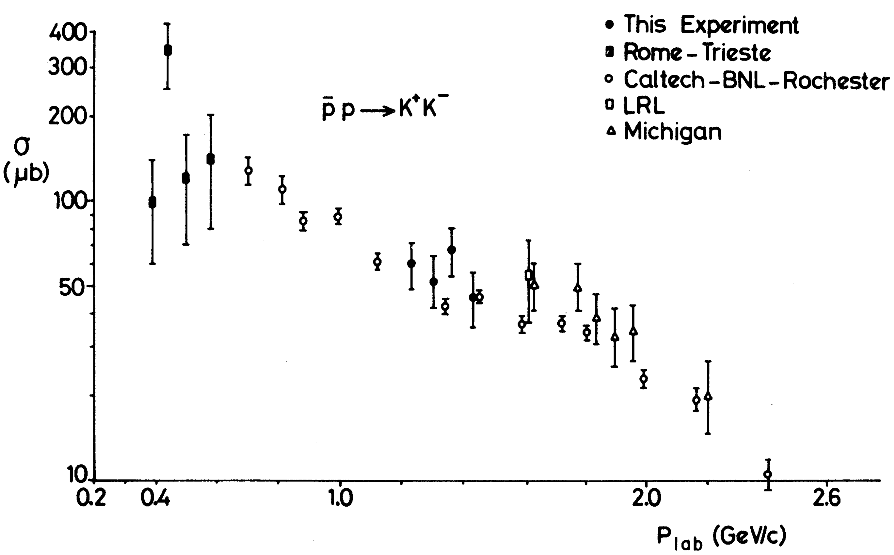

FIG. 2. Cross section vs $P_{\rm lab}$ for the reaction $\bar{p}p \rightarrow K^+K^-$.

TABLE I. Legendre coefficients for $\bar{p}p \to \pi^-\pi^+$.

Ratio \ Momentum (GeV/c)	1.23	1.30	1.36	1.43	Over-all
a_1/a_0	-0.34 ± 0.16	-0.25 ± 0.19	0.36 ± 0.18	-0.55 ± 0.19	-0.21 ± 0.09
a_2/a_0	-0.05 ± 0.22	-0.04 ± 0.25	-0.59 ± 0.25	-0.26 ± 0.26	-0.20 ± 0.12
a_3/a_0	-0.41 ± 0.22	-0.78 ± 0.23	-0.31 ± 0.28	0.28 ± 0.29	-0.35 ± 0.13
a_4/a_0	0.13 ± 0.29	0.20 ± 0.30	0.29 ± 0.35	-0.06 ± 0.40	0.14 ± 0.17
a_5/a_0	0.78 ± 0.31	0.52 ± 0.34	0.16 ± 0.34	-0.90 ± 0.35	0.61 ± 0.17
a_6/a_0	-1.03 ± 0.33	-1.23 ± 0.34	-0.69 ± 0.40	-0.50 ± 0.40	-0.91 ± 0.18
a_7/a_0	-0.17 ± 0.38	0.05 ± 0.38	0.02 ± 0.42	-0.68 ± 0.41	-0.17 ± 0.20
a_8/a_0	0.71 ± 0.40	0.04 ± 0.43	0.67 ± 0.44	1.40 ± 0.45	0.67 ± 0.22
a_9/a_0	-1.48 ± 0.43	0.50 ± 0.50	0.03 ± 0.47	0.77 ± 0.49	0.29 ± 0.24
a_{10}/a_0	0.08 ± 0.44	0.17 ± 0.48	-1.08 ± 0.47	-1.23 ± 0.53	-0.40 ± 0.24

but the data are heavily contaminated by events of higher multiplicity:

$$\bar{p}p \to \pi^+ + \pi^- + n\pi^0\text{'s}, \quad n>1 . \tag{4}$$

Figure 4 shows the distribution of missing mass squared for all events (27 451) having two charged pions and one or more neutrals. The π^0 peak is clearly visible adjacent to the multineutral background. The contamination of the three-pion fits manifests itself as follows:

(a) The distribution of missing mass squared of events fitting reaction (3) is asymmetric with a 46% excess of events above the π^0 mass.

(b) The distribution of fit probability shows a 16% excess of events with probability of less than 0.20.

(c) A fit of fractions of four-pion and five-pion phase space to the distribution of missing mass squared for no-fit events [reaction (4)] indicated no four-pion annihilations, whereas the four-prong data[6] indicate that four- and five-pion annihilations are in the ratio of 1 : 4.

It was noticed that, in 70% of all fits, the momen-

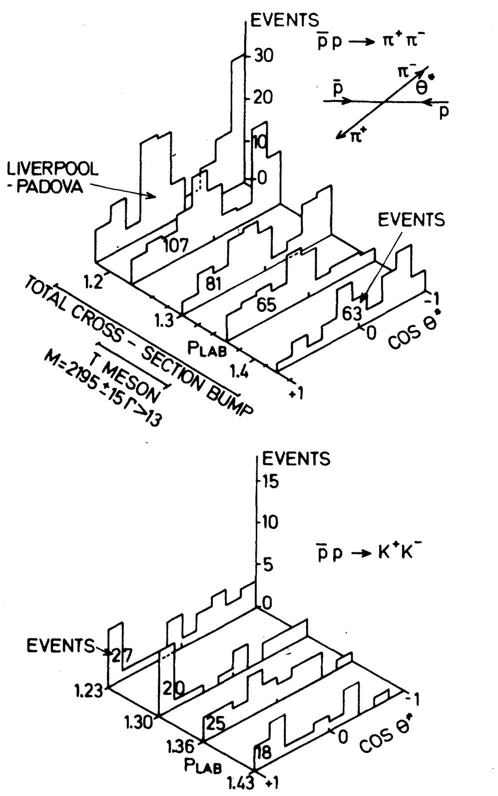

FIG. 3. Center-of-mass angular distributions for $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$. Momenta are in GeV/c.

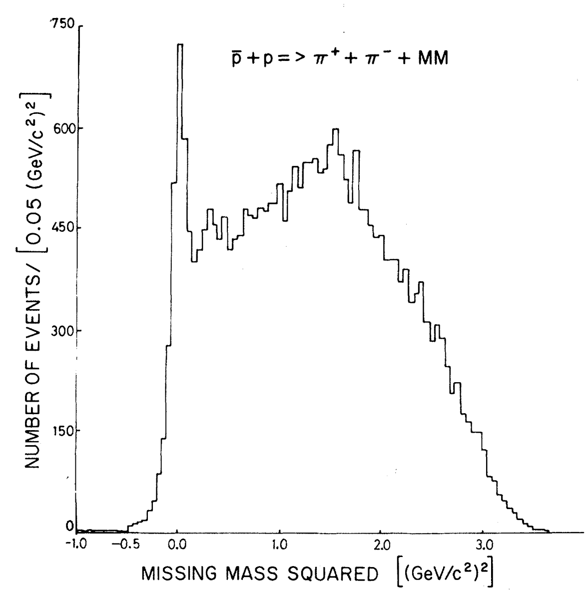

FIG. 4. Missing mass squared for the reaction $\bar{p}p \to \pi^+\pi^-$ + neutrals.

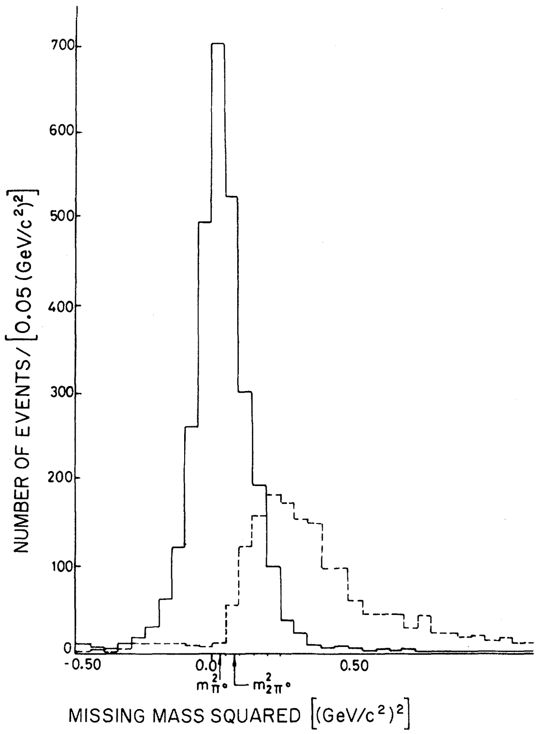

FIG. 5. Missing mass squared for the reaction $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$. The solid and dashed histograms indicate the signal and background events, respectively.

tum of outgoing tracks had been increased and that of the beam decreased relative to the measured values, compensating for the high missing mass of the contaminating events. Further, for some events, the unfitted momentum error was found to be smaller that the *fitted* momentum error for one or more tracks (of course the *percentage* errors are always decreased in fitting). These latter events were found to be almost exclusively contaminants as evidenced by the following effects of their exclusion:

(a) The asymmetry in missing mass squared was reduced to -1% (Fig. 5 shows this distribution for events accepted and rejected by the cut).

(b) The data removed were predominantly of low probability (the resultant probability distribution is flat).

(c) Further, when the data so rejected were added to the sample of reaction (4) the missing-neutral-mass distribution was fitted by 17% four-pion and 83% five-pion phase-space contributions, in agreement with the four-prong data.

This selection was further investigated with a sample of four-constraint four-pion annihilations. The four possible neutral dipion combinations were fitted as one-constraint three-pion annihilations; 80% of these faked events fitted the three-pion channel and, as shown in Fig. 6, exhibited similar behavior to the events rejected by the cut in the two-prong data. Overall, the cut enhanced the ρ and f^0 signals in the $\pi^+\pi^-\pi^0$ events, and fits to Breit-Wigner forms yielded parameters in agreement with accepted values[7] (see below).

In order to determine the amount of dipion resonance production in this channel the Dalitz-plot density distribution was fitted by maximum likelihood to the form

$$[1-f(\rho^\pm)-f(\rho^0)-f(f^0)]\phi(3\pi)+f(\rho^\pm)[f_{\rm BW}(\rho^+)+f_{\rm BW}(\rho^-)]\phi(\rho)+f(\rho^0)f_{\rm BW}(\rho^0)\phi(\rho)+f(f^0)f_{\rm BW}(f^0)\phi(f)\ ,$$

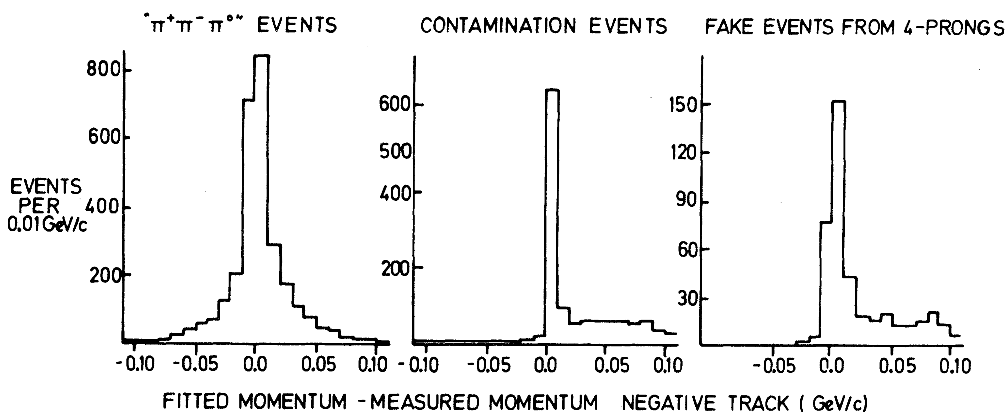

FIG. 6. Measured momentum-fitted momentum (negative track) for (a) $\pi^+\pi^-\pi^0$ events, (b) background events, and (c) events faked from four-constraint four-prongs.

where $f(x)$ are fractions of resonant contribution, f_{BW} denotes a Breit-Wigner resonance form, and the $\phi(x)$ denote the normalized phase-space factors. The dipion resonances were fitted using energy- and spin-dependent widths of the form

$$\Gamma = \Gamma_0 (q/q_0)^{2l+1} ,$$

where Γ_0 is the reduced width, q is the momentum of the π in the dipion c.m. system, q_0 is the value of q at the mass of the resonance, and l is the spin of the dipion system. The masses and widths of the charged and neutral ρ were taken to be the same. The fits were stable to the choice of starting values and yielded the following fractions for the data from all energies combined:

$$f(\rho^\pm) = (14.1 \pm 2.2)\% ,$$

$$f(\rho^0) = (14.3 \pm 1.8)\% ,$$

and

$$f(f^0) = (17.0 \pm 2.0)\% .$$

The dipion mass distributions and results of the fit are shown in Fig. 7. The fitting procedure was also applied to data obtained at individual beam momenta to determine the variation of cross sections for resonance production. With the possible exception of a relatively small $\rho^\pm$ cross section at 1.36 GeV/c, the resonance fractions and cross sections summarized in Table II are approximately constant. A compilation of the three-pion cross sections in the region is shown in Fig. 8. We estimate that the cut used to purify the data sample contributes a systematic error of the order $^{+2}_{-0}\%$ to the cross section. This is smaller than the statistical errors. We see no evidence of direct-channel effects in this reaction.

In the analysis of $\bar{p}n$ annihilations at rest to $\pi^-\pi^-\pi^+$ it has been claimed that the enhancement in the $\pi^-\pi^+$ effective mass at the ρ mass is due in

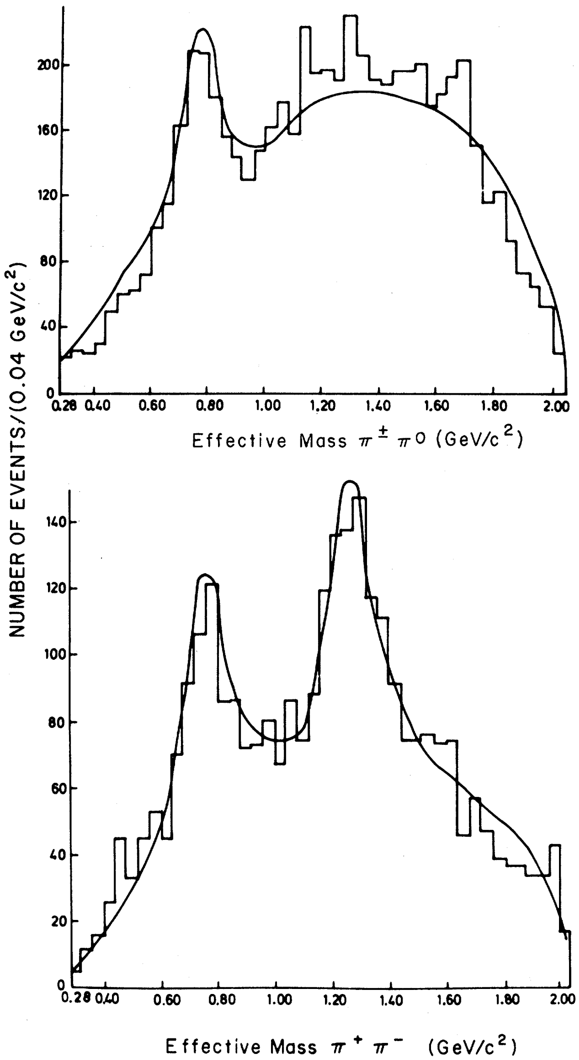

FIG. 7. $\pi^+\pi^-$ and $\pi^\pm\pi^0$ effective-mass distributions for $\bar{p}p \to \pi^+\pi^-\pi^0$.

TABLE II. $\bar{p}p$ annihilation cross sections.

Momentum / Reaction	1.23 GeV/c σ (μb)	1.30 GeV/c σ(μb)	1.36 GeV/c σ (μb)	1.43 GeV/c σ (μb)	Mean value σ (μb)
$\bar{p}p \to \pi^+\pi^-$	235 ± 23	211 ± 24	171 ± 21	153 ± 19	...
$\to K^+K^-$	59 ± 11	52 ± 11	66 ± 13	44 ± 10	...
$\to \pi^+\pi^-\pi^0$	2019 ± 75	1894 ± 78	1719 ± 72	1742 ± 71	1843 ± 46
$\to \rho^\pm\pi$	313 ± 84	308 ± 85	151 ± 82	215 ± 78	260 ± 39
$\to \rho^0\pi^0$	255 ± 61	304 ± 71	216 ± 64	251 ± 61	264 ± 32
$\to f^0\pi^0$	356 ± 71	300 ± 78	290 ± 76	295 ± 73	313 ± 38
$\to \pi^+\pi^- n\pi^0$, $n > 1$	17.66 ± 0.36 mb	17.10 ± 0.36 mb	16.74 ± 0.35 mb	15.86 ± 0.33 mb	...
$\to \rho^0 n\pi^0$, $n > 1$	...	...	...	...	624 ± 60

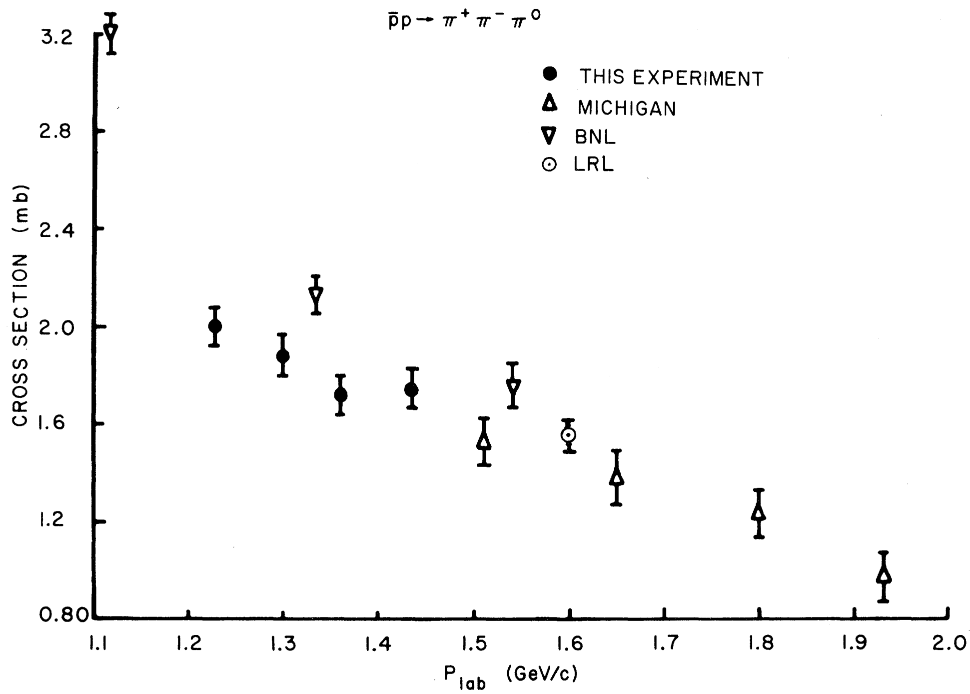

FIG. 8. Cross section vs P_{lab} for the reaction $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$.

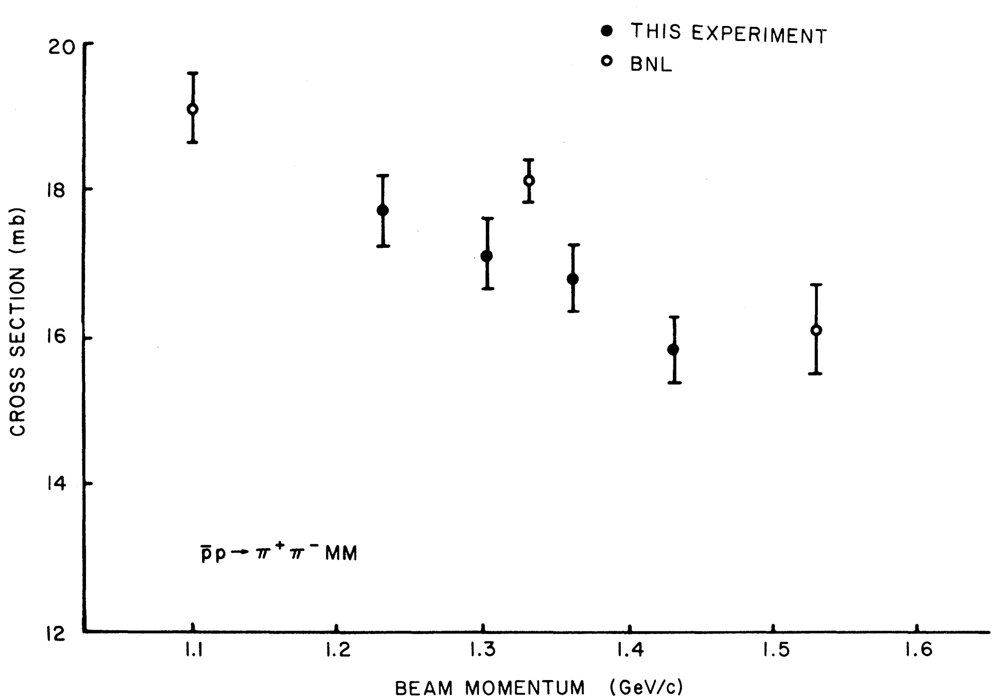

FIG. 9. Cross section vs P_{lab} for the reaction $\bar{p}p \rightarrow \pi^+\pi^-$ + neutrals.

part to the $I=0$ scalar dipion, the ϵ^0, of width about 200 MeV.[8] We performed a maximum-likelihood fit to the total data allowing the widths of the charged and neutral ρ to vary independently. The resulting fit gave $\Gamma(\rho^\pm) \sim 100$ MeV and $\Gamma(\rho^0) \sim 245$ MeV; however, the improvement in the goodness of fit is not such as to allow a definite conclusion about the presence of the ϵ^0. The $\bar{p}p$ system is an unknown mixture of the $I=0$ and $I=1$ states and the three-pion final state does not exhibit the Veneziano holes evident in the Dalitz plot for $\bar{p}n$ annihilations (pure $I=1$) into three pions. In this case, the use of the Veneziano five-point function involves nine independent amplitudes; thus no attempt to fit our data using a Veneziano model has been made.

$\bar{p}p \to \pi^+\pi^- +$ NEUTRALS

The majority of two-prong annihilations occur with more than one accompanying neutral. The missing-mass distributions (Fig. 4) at individual beam momenta are very similar. In Fig. 9, the cross-section variation with incident momentum as determined in our experiment is compared with the data of Kalbfleisch *et al.*,[9] who claimed evidence of a bump in this channel cross section possibly corresponding to a $\rho^+\rho^-\pi^0$ final state due to the T meson. Their data points are consistently higher than ours, which might be due to a differing treatment of events with identifiable K mesons. The very good agreement between the two experiments for the elastic scattering cross section[3,10] makes it unlikely that the difference is due to normalization problems. We conclude that there is no significant evidence of structure near the T meson in the $\pi^+\pi^-+$neutrals channel. Figure 10 shows the effective-mass distribution for the multineutral events after separation from the $\pi^+\pi^-\pi^0$ events. The ρ^0 signal is clearly visible above a large, rapidly falling background; probably a small f^0 signal is also present. An estimate of the ρ^0 cross section has been made using the simple background shown; the ρ^0+multineutrals contribution is $(3.7\pm0.4)\%$ of the $\pi^+ + \pi^-$ $+$multineutrals channel. The missing-mass distribution for events in the ρ^0 region shows some evidence for the $\rho^0 f^0$ and $\rho^0\eta$ final states; similarly, the cut on the η mass indicates a small $f^0\eta$ signal. The significant annihilation cross sections observed in this experiment are summarized in Table II.

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

In $\bar{p}p$ annihilations into seven pions, in a neighboring energy range,[11] evidence has been presented for a cascade decay of the D meson:

$$D \to \delta\pi \to \eta\pi\pi \ .$$

Other authors[12] have claimed that the enhancement

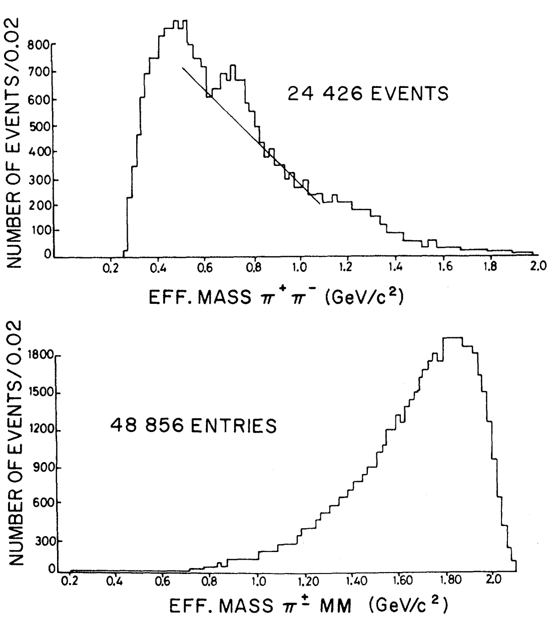

FIG. 10. Effective-mass distributions for the reaction $\bar{p}p \to \pi^+\pi^- +$ neutrals, with $\pi^+\pi^-\pi^0$ events removed.

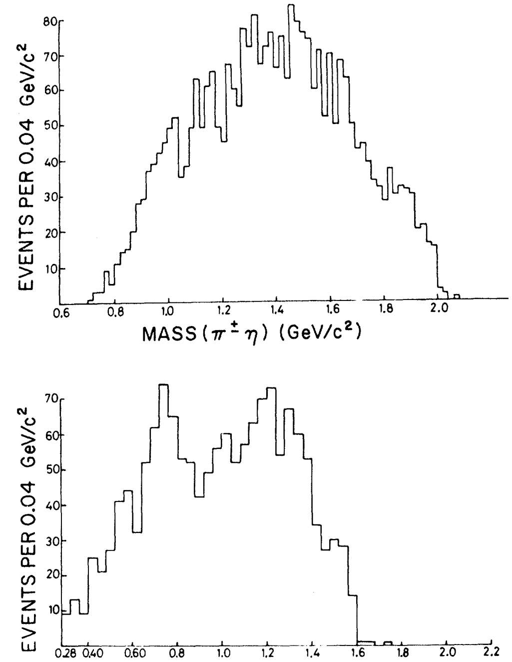

FIG. 11. $\pi^+\pi^-$ and $\pi^\pm\eta$ masses for $\bar{p}p \to \pi^+\pi^-\eta$.

at the δ mass is merely a reflection of strong ω^0 production. It is thus of interest to look for the δ in states in which the effects of reflections from ω^0 production are suppressed. Analysis of the five-pion final state indicates a $\pi^+\pi^-\eta$ contribution with η decay in the $\pi^+\pi^-\pi^0$ mode[13]; from this we would expect to see about 600 events ($\sigma \approx 400$ μb) with neutral η decay. This could indeed be consistent with the signal seen in the distribution of missing mass in Fig. 4, depending on how one estimates the large and uncertain multi-π^0 background. All the two-prong events were tried against the $\pi^+\pi^-\eta$ hypothesis, yielding 4305 kinematical fits with probability greater than 0.1%. After application of the selection criteria used previously to isolate the three-pion annihilations, and excluding events which had been selected as such, 1471 $\pi^+\pi^-\eta$ candidates remained. Figure 11 shows the $\pi^+\pi^-$ and $\pi^\pm\eta$ effective-mass distributions for these events. There is a clear ρ^0 peak and probably an f^0 contribution in the $\pi^+\pi^-$ mass distribution. From a hand-drawn background in the $\pi^\pm\eta$ mass spectrum near 970 MeV, one can set an upper limit for $\delta\pi$ production:

$$\sigma(\bar{p}p \to \delta\pi) < 80 \ \mu\text{b} .$$

The $\eta\pi$ mass distributions are much the same at each of the four energies and in both charge states.

SUMMARY

In conclusion, one can say that at the level of statistics of the present experiment there is no significant evidence of direct-channel T-meson formation in the two-prong annihilation channels nor in the nonannihilation channels.[3] Future counter experiments on the $\pi^+\pi^-$ and K^+K^- final states should prove most interesting in view of the structure indicated by our low-statistics angular distributions.

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