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Study of the $\rho(1710)$ at 8.0 and 18.5 GeV/c*

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We have studied the reaction $\pi^- p \to p\rho^-(1710) \to p\pi^+\pi^-\pi^-\pi^0$ at 8.0 and 18.5 GeV/c. Evidence is presented for the dominance of the $\rho^-\rho^0$ decay mode. An upper limit of 39% for $A\pi$ decay relative to all 4π decay modes is determined for the $\rho^-(1710)$. Assuming only $\rho\rho$ and $\omega\pi$ decay modes contribute, we find $[\rho(1710) \to \rho\rho]/[\rho(1710) \to \text{all } 4\pi] = (78 \pm 33)\%$ and $[\rho(1710) \to \omega\pi]/[\rho(1710) \to \text{all } 4\pi] = (22 \pm 8)\%$. If the $\rho(1710)$ is identical to the $g(1680)$, we find $(g \to 2\pi)/(g \to 4\pi) = 0.35 \pm 0.11$. The mass and width of the $\rho(1710)$ determined from the $(4\pi)^-$ mass spectrum are 1.687 ± 0.020 GeV and $0.169^{+.070}_{-.048}$ GeV, respectively. The production cross section is determined as a function of energy and, if a function of the form $\sigma = A_{\text{lab}}^{-n}$ is assumed, we find $n = 1.4^{+0.5}_{-0.3}$. The distribution of four-momentum transfers, $t' = t - t_{\min}$, for $\rho(1710)$ production is characterized by a two-slope distribution with $\alpha_1 \approx 9.6$ (GeV/c)$^{-2}$ for $t' \lesssim 0.3$ (GeV/c)^2 and $\alpha_2 \approx 2.1$ (GeV/c)$^{-2}$ for $t' \gtrsim 0.3$ (GeV/c)^2.

I. INTRODUCTION

Meson spectroscopy in the 1600–1800 MeV/c^2 mass region has been under rather intensive study[1–21] for some time now. Although much study has been devoted to this region, the results are sufficiently complicated that even the number of resonances is not known. For example, for states with even g parity, clear enhancements have been observed in the 2π and 4π mass distributions. Since the 4π enhancement has an average mass[22] ($m = 1721 \pm 10$ MeV) and width ($\Gamma = 128 \pm 21$ MeV) rather different from the 2π enhancement ($m = 1682 \pm 12$ MeV and $\Gamma = 157 \pm 23$ MeV), it is not certain whether one or more resonances are involved. There is strong evidence[17,18,20] that the 2π resonance has $J^P = 3^-$, but no measurement has been reported for the 4π resonance. The situation is further complicated by the fact that the peak in the $\omega\pi$ subset of the 4π spectrum has an average mass[22] of 1634 MeV and by the fact that the charged 2π mode has an average mass[22] some 40 MeV lower than the value of 1682 MeV quoted above for the $\pi^+\pi^-$ mode. Finally, there is some evidence[19] for an $I = 0$ even g parity resonance in this region as well as for an $I = 1$ 4π resonance at ≈ 1630 MeV for which no corresponding 2π mode is observed.[15,21]

It is likely that the confused situation will be cleared up only after many careful experiments are carried out. The observation of more than two enhancements or of the same enhancement at several energies in the same experiment should produce some clarification. Careful analyses and new approaches in analysis may also be fruitful.

In this paper, we will analyze the reaction

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

at two momenta: 8.0 and 18.5 GeV/c. The main purpose of the experiment is to study the properties of the four-pion enhancement at about 1710 MeV which we shall refer to as the $\rho(1710)$. Using data at two different energies allows us to study the production cross section as a function of energy and to combine the data to get more accurate results for the resonance parameters and branching ratios. In Sec. II we give the experimental details. Section III contains our analysis and conclusions.

II. PROCEDURE

The data used in this analysis come from two experiments done in the 80-in. hydrogen bubble chamber at Brookhaven National Laboratory. The first of these was an experiment consisting of 50 000 pictures of $\pi^- p$ interactions at 8 GeV/c and the second was one of 180 000 pictures of $\pi^- p$ interactions at 18.5 GeV/c. The film in each experiment was scanned for all four-prong events, which were then measured and analyzed using the standard geometry program HAG[23] and kinematically fitted using GRIND.[24] All events were checked for consistency between fitted hypotheses and ionization. Further details of the analysis are discussed elsewhere.[25,26] The procedure has resulted in 1970 events at 8 GeV/c and 3166 events at 18.5 GeV/c which fit reaction (1) with acceptable values[25,26] of χ^2, which are consistent with ionization, and which fit no other hypothesis. This sample has been shown[25,26] to have contamination from reactions other than reaction (1) less than 10%, and is the sample which is used in the analysis to follow.

III. ANALYSIS

A. Four-Pion Mass Spectrum

Figure 1(a) shows the combined four-pion mass spectrum for our data sample. The shaded section shows the 18.5-GeV/c data alone. The arrows at 1260 MeV and 1700 MeV show the nominal positions for the B meson and the $\rho(1710)$ meson. Peaks are present in the combined sample as well as the individual subsets in both regions.

Figure 1(b) is the four-pion mass spectrum resulting when one $\pi^+\pi^-\pi^0$ is required to have an effective mass in the ω^0 region (chosen to be in the range 0.720 to 0.840 GeV). The B meson, as is well known, is dominantly an $\omega\pi$ effect, and dominates Fig. 1(b). There is also an apparent $\omega\pi$ decay mode of the $\rho(1710)$ which is discussed further below.

The $\rho^-\rho^0$ mass spectrum is shown in Fig. 1(c). An entry is made in this figure for every event in Fig. 1(a) which simultaneously satisfies the requirements $0.66 \le M(\pi^+\pi_1^-) \le 0.86$ GeV and $0.66 \le M(\pi_2^-\pi^0) \le 0.86$ GeV. The presence of the peak at about 1700 MeV indicates the possibility of a $\rho\rho$ decay mode for the $\rho(1710)$ and is also discussed in detail below.

The data of Figs. 1(a)–1(c) have been fitted to the sum of background and Breit-Wigner distributions using hand-drawn background curves. These background curves are shown as dashed lines in the figure. The form used in the fits was the expression

$$\frac{dN}{dm} = f_{\rm BG}\left(1 + \frac{a(\Gamma/2)^2}{(m-m_0)^2 + (\Gamma/2)^2}\right).$$

Here m is the 4π effective mass, $f_{\rm BG}$ is the background curve, m_0 is the resonant mass, a is the intensity, and Γ is the resonant width which was taken independent of m. Maximum-likelihood fits were carried out varying the parameters a, m_0, and Γ. The results of these fits are given in Table I. Our values for the B-meson mass are just over 1 standard deviation above the current world average[22] of 1.233 GeV, the width 1–2 standard deviations above the current world average[22] of 0.104 GeV. If the $\rho\rho$ and $\omega\pi$ peaks are the same resonance, which is consistent with our data, then the $\rho(1710)$ mass and width should be taken from the uncut data (the "all" sample in Table I). These values are consistent with the current world averages[22] of 1.712 GeV and 0.128 GeV for the $\rho(1710)$ mass and width.

B. Decay Modes

We now turn to the question of the $\rho(1710)$ decay modes. Previous work using only our 8-GeV/c

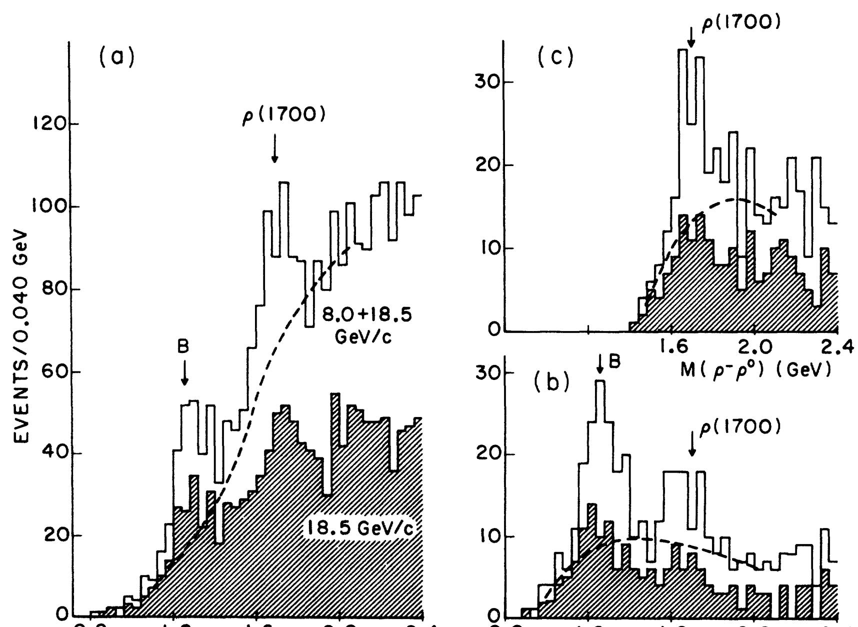

FIG. 1. (a) The $\pi^+\pi^-\pi^-\pi^0$ effective-mass distribution for the 18.5-GeV/c data (shaded), and the combined 8.0- and 18.5-GeV/c data. (b) The $\omega^0\pi^-$ effective-mass distributions for the same data samples. The ω^0 requirement is $0.720 \le M(\pi^+\pi^-\pi^0) \le 0.84$ GeV. (c) The $\rho^-\rho^0$ effective-mass distribution for the same data samples. Here it is required that both $\pi\pi$ combinations satisfy the cut $0.660 \le M(\pi\pi) \le 0.860$ GeV.

TABLE I. Fitted resonance parameters.

Data sample	B meson Mass (MeV)	B meson Width (MeV)	ρ(1710) Mass (MeV)	ρ(1710) Width (MeV)
All	1.251 ± 0.012	$0.166^{+0.033}_{-0.036}$	1.687 ± 0.020	$0.169^{+0.070}_{-0.048}$
$\rho^-\rho^0$	...	...	1.685 ± 0.014	$0.125^{+0.083}_{-0.035}$
$\omega^0\pi^-$	1.248 ± 0.014	$0.148^{+0.045}_{-0.030}$	1.666 ± 0.050	$0.194^{+0.094}_{-0.060}$

data has indicated[8] the presence of a strong $\rho\rho$ decay mode. Other experiments have reached rather contradictory results, one concluding that the $A\pi$ decay mode[7] dominates and another[16] that the $\rho\rho$ (or $\rho\pi\pi$) mode dominates. Figure 2 shows one way in which we can reach some conclusions regarding this question. This figure shows the $\pi^+\pi^-$, $\pi^-\pi^0$, and $\pi^+\pi^0$ effective-mass distribution for the combined data for events in the $\rho(1710)$ region $[1.640 \leq M(4\pi) \leq 1.760$ GeV$]$. The data show clear ρ^0 and ρ^- signals, but no ρ^+ signal. This result is consistent with the data of Ballam *et al.*[16] and rules out the dominance of an $A\pi$ decay mode for the $\rho(1710)$. [If the $\rho(1710)$ decayed to $A\pi$ 100% of the time, one should observe identical ρ signals in Figs. 2(a), 2(b), and (c).] To get a quantitative upper limit on the $A\pi$ decay mode, we estimate the ρ^+ signal in Fig. 2(c) to be no more than nine events. Since the ρ^+ signal represents $\frac{1}{4}$ of the $A\pi$ decays, we estimate an upper limit of 36 $\rho(1710)$ events. This represents 39% of the $\rho(1710)$ events with $1.640 \leq M(4\pi) \leq 1.760$ GeV, and thus we find

$$\frac{\rho(1710) \rightarrow A\pi}{\rho(1710) \rightarrow \text{all } 4\pi} < 0.39 .$$

We now turn to the $\rho\rho$ decay mode. We will first make some qualitative observations which indicate the presence of this decay mode and then make a quantitative estimate of this branching ratio.

Figure 1(c), the $\rho^-\rho^0$ mass distribution, indicates the strong possibility of a $\rho^-\rho^0$ decay mode of the $\rho(1710)$. A previous analysis[8] of the 8.0-GeV/c data alone showed that the peak at ~1700 MeV is due to true double-ρ events rather than $\rho\pi\pi$ background when one makes a $\rho\rho$ cut. We note that the $\rho(1710)$ signal in Fig. 1(c) is roughly 40% that of Fig. 1(a), a factor very close to that expected when one makes the ρ cuts if the $\rho\rho$ decay mode is the only one. We note further that Fig. 2 shows strong ρ^0 and ρ^- signals, again a necessary condition for a $\rho^-\rho^0$ decay. Figure 3 shows a way to make a quantitative estimate of this branching ratio. Here we show the $\rho^-\rho^0$ mass distribution for various ρ-defining cuts on the $\pi\pi$ masses. The object is to study quantitatively the dependence of the $\rho(1710)$ signal on this cut. We can compare the experimental data with the simple prediction based on a Breit-Wigner shape for the ρ-meson decay. Table II shows the prediction for the percent of $\rho\rho$ events

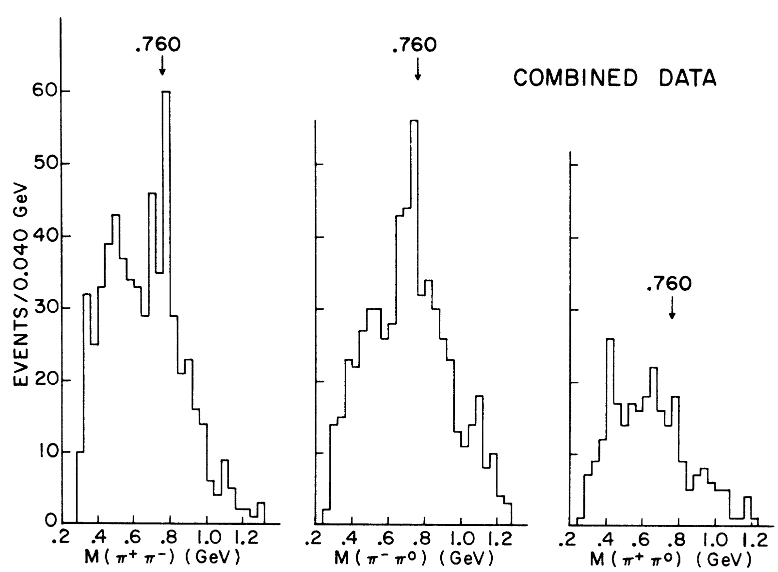

FIG. 2. The dipion effective-mass distributions for events in the combined 8.0- and 18.5-GeV/c data which are in the $\rho(1710)$ region defined to be $1.640 \leq M(\pi^+\pi^-\pi^-\pi^0) \leq 1.760$ GeV.

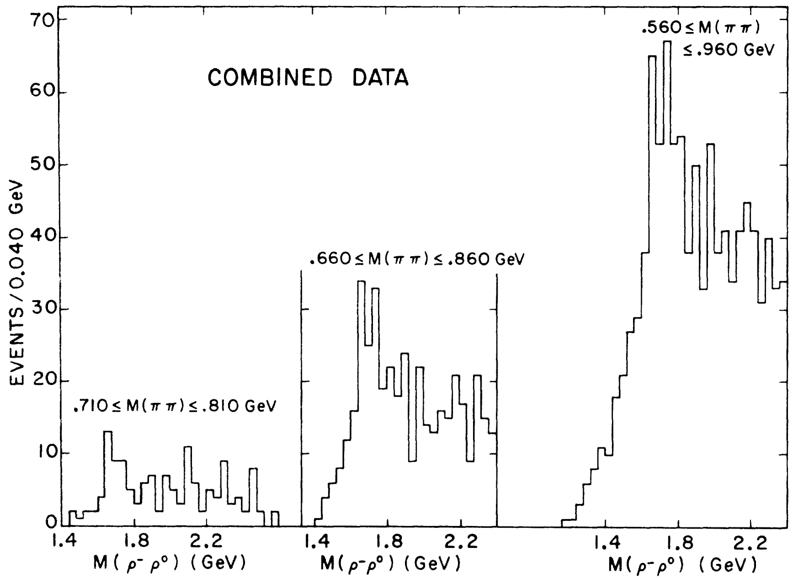

FIG. 3. The $\rho^-\rho^0$ effective-mass distributions for various ρ-defining cuts for the combined 8.0- and 18.5-GeV/c data (see text).

which should survive the various cuts, as well as the prediction for the percent of $\rho\pi\pi$ events which should survive the cuts. We have assumed the ρ to have a mass of 0.760 GeV with a width of 0.125 GeV consistent with currently accepted parameters.[22] (The $\rho\pi\pi$ prediction is based on a ρ cut and a $\pi\pi$ background cut. The $\pi\pi$ background cut was taken to be a smooth hand-drawn curve through the data of Fig. 2 ignoring the ρ signal.) Table II also shows the experimental results, which agree very closely with the $\rho\rho$ prediction. The quantitative result, based on the ratio of the signal in Fig. 3 to that in Fig. 1(a), is

$$\frac{\rho(1710)\to\rho\rho}{\rho(1710)\to \text{all } 4\pi}=1.0\pm0.25\,.$$

[Figures 3(a), 3(b), or 3(c) all lead to the same value of this ratio, but with different errors. The quoted error is based on the data of Fig. 3(b).]

In order to study the $\omega\pi$ branching ratio, we determine the $\omega\pi$ signal from the fit to Fig. 1(b) and compare to the over-all signal of Fig. 1(a). Since the dominant decay mode is $\rho^-\rho^0$, there will be a very small background of non-ω^0-associated $\rho(1710)$ events in the ω^0 mass band. To within the errors quoted here, this background is compensated for by the true ω^0 events excluded by the ω^0 mass cut, and no correction is made. We find

$$\frac{\rho(1710)\to\omega^0\pi}{\rho(1710)\to \text{all } 4\pi}=0.24\pm0.08\quad(\omega^0\to\pi^+\pi^-\pi^0 \text{ only})\,.$$

This result is shown in Table III along with our other branching ratios. We also show in Table III the best fit to these data assuming that the $\rho\rho$ and $\omega\pi$ decay modes comprise 100% of the $\rho(1710)$ decays.

C. Production Characteristics

We now discuss the production characteristics of the reaction $\pi^-p\to p\rho(1710)$. We define t to be the four-momentum transfer from the initial- to the final-state proton. If t_{min} is the minimum value of t for a given 4π mass, we define $t'=t-t_{min}$. Figure 4 shows the t' distribution for the combined data in the $\rho(1710)$ region. The presence of two slopes

TABLE II. Percentage of events remaining for various hypotheses and for the experimental data as a function of the cut on the $\pi\pi$ effective masses. The "theory" assumes that 100% of the events decay via the hypothesized mode.

$\pi\pi$ mass cut	$\rho\rho$ decay (theory)	$\rho\pi\pi$ decay (theory)	Experiment
0.710–0.810 GeV	18.4%	5.6%	(20 ± 7.3)%
0.660–0.860 GeV	41.5%	15.5%	(42 ± 13)%
0.560–0.960 GeV	63.2%	39%	(64 ± 22)%

TABLE III. $\rho(1710)$ branching ratios.

Decay mode	Ratio (unconstrained)	Ratio (constrained) [a]
$\frac{A\pi}{\text{all } 4\pi}$	<0.39	0
$\frac{\rho\rho}{\text{all } 4\pi}$	1.0 ± 0.25	0.78 ± 0.33
$\frac{\omega\pi(\omega \to \pi^+\pi^-\pi^0 \text{ only})}{\text{all } 4\pi}$	0.24 ± 0.08	0.22 ± 0.08
$\frac{\pi^-\pi^0}{\pi^+\pi^-\pi^-\pi^0}$	0.35 ± 0.11	...

[a] The constraint imposed was that the $(\rho\rho) + (\omega\pi)$ ratios added to 1.0.

is apparent in the figure.[27] Fits of the form $d\sigma/dt' = Ae^{-\alpha t'}$ in the two regions [$0.0 \leq t' \leq 0.3$ (GeV/c)^2 and $0.3 \leq t' \leq 1.0$ (GeV/c)^2] yield slopes of 9.6 (GeV/c)$^{-2}$ and 2.1 (GeV/c)$^{-2}$, respectively. Figure 5(a) shows the $\rho^-\rho^0$ mass distribution for $t' > 0.3$ (GeV/c)^2. The $\rho(1710)$ signal in this high-t' region is clear and is, in fact, proportional to the total number of high-t' events. Figure 5(b) shows the $\rho^-\rho^0$ mass distribution for the low-t' events (shaded) as well as for the total data sample. We conclude that the entire distribution in Fig. 4 is characteristic of $\rho(1710)$ production and that the $\rho(1710)$ signal/noise ratio is *not* enhanced by selecting low-momentum-transfer events.

The $\rho(1710)$ production cross sections for the 8.0- and 18.5-GeV/c data are given in Table IV.

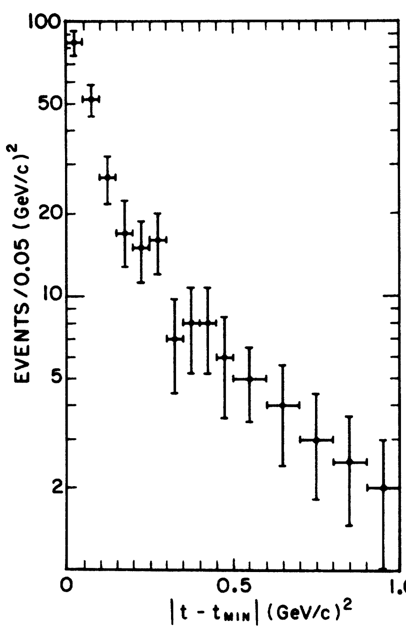

FIG. 4. The distribution in $t - t_{\min}$ for events in the $\rho(1710)$ region for the combined 8.0- and 18.5-GeV/c data.

The cross section decreases such that if one parametrizes the energy dependence by the relation

$$\sigma(p_{\text{lab}}) = A(p_{\text{lab}})^{-n},$$

we find $n = 1.4^{+0.5}_{-0.3}$.

In Table IV we quote an upper limit to the cross section $\pi^+p \to p\rho^+(1710)$ at 18.5 GeV/c determined from another exposure. That data show no evidence of a narrow peak at the $\rho^+(1710)$ mass.

D. Decay Angular Distributions

The t' distribution, although somewhat complicated, is consistent with a one-particle-exchange picture. In fact, it is probably consistent with one-

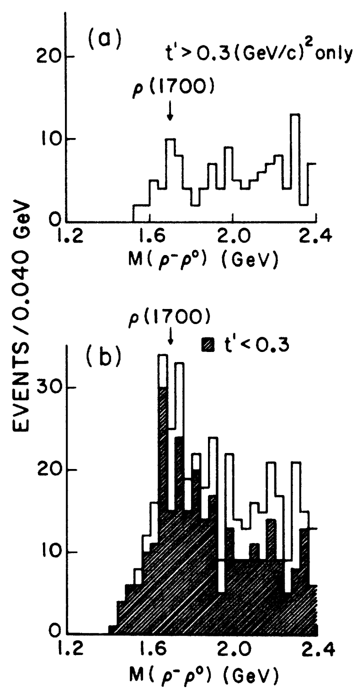

FIG. 5. The $\rho^-\rho^0$ effective-mass distribution for different regions of $t' = t - t_{\min}$. (a) $t' > 0.3$ (GeV/c)^2; (b) shaded, $t' < 0.3$ (GeV/c)^2; unshaded, all events.

TABLE IV. $\rho(1710)$ production cross sections.

Reaction	Momentum (GeV/c)	Cross section (mb)
$\pi^- p \to p\rho^-(1710)$ $\to (\pi^+\pi^-\pi^-\pi^0)$	8.0	0.062 ± 0.014
$\pi^- p \to p\rho^-(1710)$ $\to (\pi^+\pi^-\pi^-\pi^0)$	18.5	0.018 ± 0.005
$\pi^+ p \to p\rho^+(1710)$ $\to (\pi^+\pi^+\pi^-\pi^0)$	18.5	<0.020

pion exchange with absorption.[20] In addition, the energy dependence of the $\rho(1710)$ production cross section is also consistent with this picture. We have therefore studied the $\rho(1710)$ decay angular distributions for events surviving the $\rho\rho$ cuts. The angles studied were the $\rho(1710)$ decay angle, the $\rho^0(760)$ decay angle, and the $\rho^-(760)$ decay angle. We have also examined all the correlations between these angles. In all cases, the angular distributions were *isotropic* and consistent with *no correlations*.

E. Comparison of $g^- \to (2\pi)^-$ and $\rho^-(1710) \to (4\pi)^-$ Data

In an earlier analysis based on the 8-GeV data alone, we did not observe the g^- and set an upper limit to the branching ratio

$$R = \frac{g^- \to (2\pi)^-}{\text{“}g^-\text{”} \to (\pi^+\pi^-\pi^-\pi^0)} < 0.48$$

at the 90% confidence level. Since that result, values of 0.8 ± 0.1 were reported[12,18] for the ratio. More recently, results consistent with our earlier result have been published.[16,20] These values are $R < 0.12$ and $R = 0.22 \pm 0.04$. (This latter number is based on a one-pion-exchange fit.) In order to determine this number in this experiment, we use the published[20] cross-section summaries for the reaction $\pi^\pm p \to g^\pm p$, $g^\pm \to \pi^\pm\pi^0$. From these data, we find R at 8.0 and at 18.5 GeV/c to be 0.41 ± 0.15 and 0.28 ± 0.16, respectively. Combining these we find

$$R = 0.35 \pm 0.11 .$$

The question still remains as to whether the 2π and 4π resonances are in fact decay modes of the same resonance. Ballam *et al.*[16] found $R < 0.12$ at 16 GeV/c. Their result contrasted with values of 0.7 ± 0.18 and 0.8 ± 0.15 at 7 GeV/c (Ref. 12) and 8 GeV/c (Ref. 18), and they concluded that the 2π and 4π enhancements were in fact different. Since we are using published cross sections to find R, our own data do not bear directly on this question.

ACKNOWLEDGMENTS

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[27]The individual data samples are each consistent with the over-all data sample. Thus the two slopes are not caused by adding two different t' distributions together.

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Properties of $K\bar{K}$ and $K\bar{K}\pi$ Systems and Diffraction Dissociation*

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We present data on the $K\bar{K}$ system which is produced in the interaction of 7-GeV/c pions with nucleons. The neutral $K\bar{K}$ system is produced with a relatively large cross section, and the characteristics of the reaction seem consistent with one-pion exchange. The charged $K\bar{K}$ system is produced with a smaller cross section and is not dominated by one-pion exchange. The neutral $K\bar{K}$ system is dominated by an S-wave $K\bar{K}$ interaction up to a dikaon mass of about 1.3 GeV/c^2. If one examines the neutral $K\bar{K}$ system produced in conjunction with a π meson, the characteristics of the interaction seem to indicate diffraction dissociation as the production mechanism. The cross section for production of $\pi+(K\bar{K})^0$ is of the order of 150 μb. The system consisting of $\pi+(K\bar{K})^\pm$ is dominated by a K^+K^{*-} amplitude. The cross section for the production of the $\pi(K\bar{K})^\pm$ system is four or five times smaller than for the $\pi(K\bar{K})^0$ system. Both the $\pi(K\bar{K})^0$ and the $\pi(K\bar{K})^\pm$ systems seem to be diffractively produced.

This paper contains discussion of the $K\bar{K}$ and $\pi K\bar{K}$ systems formed in π-nucleon collisions at 7 GeV/c. We discuss these two systems together since they are intimately related. The $K\bar{K}$ system can have isospin 0 or 1 and can be in natural-parity states of 0^+, 1^-, 2^+, 3^-, etc. We are concerned primarily with states that can be reached by one-pion exchange since these states will be made with relatively large cross sections in π-nucleon collisions. We are particularly concerned