DETAILED STRUCTURE OF THE REACTIONS IN $\bar{p}p \rightarrow \pi^+\pi^-$ AND $\bar{p}p \rightarrow K^+K^-$ FROM 0.7 TO 2.4 GeV/c *

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Differential cross sections for the reactions $\bar{p}p \rightarrow \pi^+\pi^-$ and $\bar{p}p \rightarrow K^+K^-$ have been measured in the angular region $0.65 \lesssim |\cos\theta_{\text{c.m.}}| < 1.0$ at 13 momenta between 0.7 and 2.4 GeV/c. These cross sections have been combined with those of Fong et al. for $|\cos\theta_{\text{c.m.}}| \lesssim 0.70$ to give complete folded angular distributions. The data are consistent with resonances in the $J=3$ and $J=5$ states.

In this and the following Letter we report on the differential cross sections for the annihilation of antiprotons by protons into two-pion and two-kaon final states in the momentum interval from 0.7 to 2.4 GeV/c. The angular region covered was $0.65 \lesssim |\cos\theta_{\text{c.m.}}| < 1.0$, where the signs of the two particles in the final state were distinguished only for the region $0.85 \lesssim |\cos\theta_{\text{c.m.}}| < 1.0$. These data have been combined with the results from a previous California Institute of Technology--Brookhaven National Laboratory[1] collaboration covering the angular region $|\cos\theta_{\text{c.m.}}| \lesssim 0.7$ to give accurate folded $[d\sigma/d\Omega(\theta_{\text{c.m.}}) + d\sigma/d\Omega(\pi-\theta_{\text{c.m.}})]$ differential cross sections at 13 different momenta.[2]

This experiment was performed in the partially separated G-10 beam of the Brookhaven alternating-gradient synchrotron simultaneously with an experiment measuring the backward elastic scattering of antiprotons from protons.[3] Antiprotons were selected using a liquid-radiator differential Cherenkov counter[4] as well as time of flight below 1 GeV/c. The flux varied between 5×10^2 and 4×10^4 antiprotons/pulse, and the $\pi/\bar{p}$ ratio varied between 1 and 15. The $\Delta p/p$ of the beam was $\pm 2.0\%$, but a hodoscope of seven counters at the mass slit gave an effective momentum resolution of $\pm 1.0\%$.

The apparatus used to measure $K^\pm p$ backward scattering[5] was modified to accommodate a 15-in.-long liquid-hydrogen target, and additional counters were installed so that this experiment would overlap that of Fong et al.[1] Also additional counter information was recorded with each event so that the sign of particles could be determined for those events which traversed the magnet but not the wire chambers downstream of the magnet.

In the interval $|\cos\theta_{\text{c.m.}}| \gtrsim 0.96$ two-body annihilation events were chosen by three requirements: (1) Incoming and outgoing particles had to be coplanar to within 10 mrad, (2) the angle between outgoing particles had to satisfy proper kinematics to within 10 mrad, and (3) the momentum of the forward particle had to agree with the proper kinematical momentum to within ~60 MeV/c. Outside this interval only requirements (1) and (2) could be used. Accurate vertex definition ($\lesssim 5$ mm) eliminated the need for emply-target subtraction.

In this experiment the analysis programs and spark-chamber system parameters were similar to those used in the K^+p backward scattering experiment.[3] A Monte Carlo calculation was used to obtain solid angles and to correct for outgoing meson decays, multiple scatters, and nuclear interactions in the hydrogen target and detection system. We believe that the absolute normalization is known to $\pm 10\%$, and any remaining systematic error varies slowly with momentum. Additional confidence in the normalization is gained by the good agreement of this experiment and that of Fong et al.[1] in the region of overlap.

In Fig. 1 we show the folded differential cross sections for (a) two-pion annihilations and (b) two-kaon annihilations. The energy dependence of the two-pion annihilation cross section is the most striking. At the lowest momenta there is a fairly simple distribution with peaks at $|\cos\theta_{\text{c.m.}}| = 0.0$ and 1.0. At 1.45 GeV/c a second dip begins to appear at $|\cos\theta_{\text{c.m.}}| \approx 0.85$, and then up to 2.0 GeV/c there are two very pronounced dips which change with energy. This double-dipped distribution is also seen in the energy-averaged data of Chapman et al.[6] Finally, at the highest momenta the peak at $|\cos\theta_{\mathrm{c.m.}}|=0.0$ rapidly falls away. The two-kaon annihilations also show prominent energy-dependent changes, particularly in the vicinity of 1.0 GeV/c. However, the

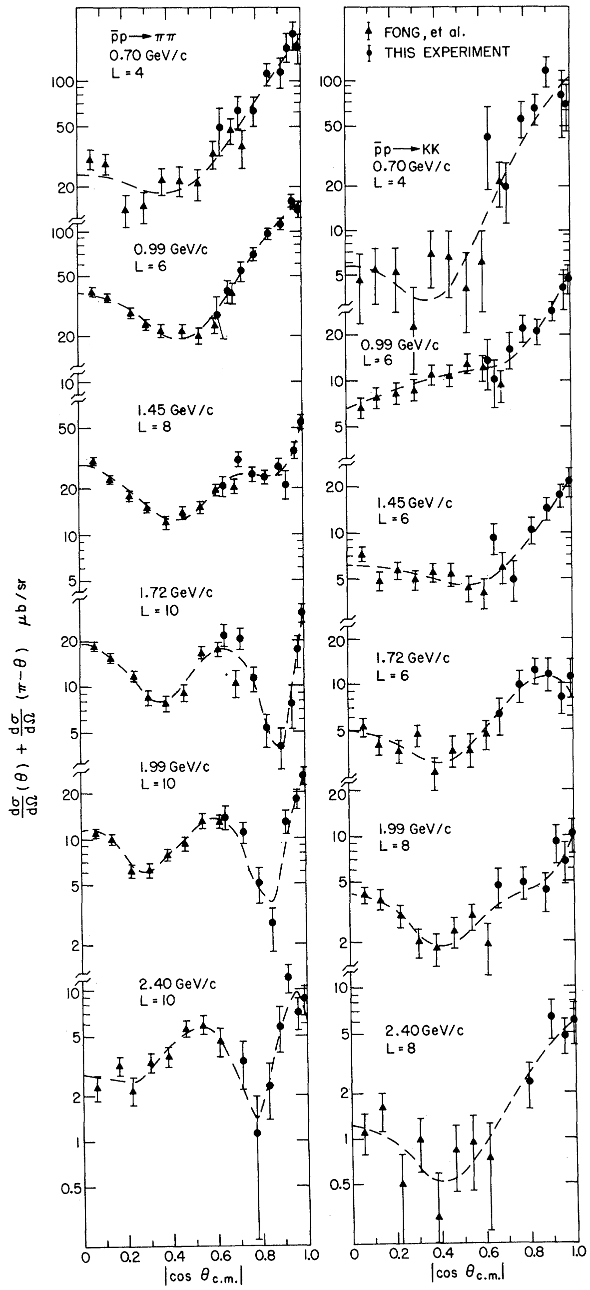

FIG. 1. Folded differential cross sections $[d\sigma/d\Omega(\theta_{\mathrm{cm}})+d\sigma/d\Omega(\pi-\theta_{\mathrm{cm}})]$ for $\bar{p}p\to\pi^+\pi^-$ and $\bar{p}p\to K^+K^-$ at six representative momenta between 0.7 and 2.4 GeV/c. All errors shown are statistical. The dashed curves through the data points are the Legendre polynomial fits described in the text.

two-kaon channel does not develop the double-dipped angular distributions observed for the two-pion channel. Since there are no G-parity restrictions on two-kaon final states there are twice as many states in the K channel, and the apparently simpler distributions may be the result of cancellations which do not occur in the two-pion channel.

We have fitted the folded differential cross sections with a series of even orthogonal (Legendre) polynomials,

$$\frac{d\sigma}{d\Omega}(\theta_{\mathrm{c.m.}})+\frac{d\sigma}{d\Omega}(\pi-\theta_{\mathrm{c.m.}}) = \sum_{l=0}^{L} a_l P_l(\cos\theta_{\mathrm{c.m.}}),\quad l \text{ even},\qquad (1)$$

since odd terms cannot contribute to the folded distributions. Between four and six terms are needed to fit the two-pion annihilations, and between three and five terms are required for the two-kaon annihilation. Chi-squared probabilities of the fits were always greater than 5%. These fits are indicated by the dashed lines in Fig. 1. The first term of these expansions when multiplied by 2π yields the total cross section for the two-body annihilations, which are shown in Fig. 2 along with results from other (bubble chamber) experiments.[6-8] In Fig. 3 we show the higher coefficients of the Legendre-polynomial expansions for the two-pion and two-kaon channels. In both cases we note strong momentum-dependent behavior.

The two-pion angular distributions shown in Fig. 1 seem to indicate the dominance of one set

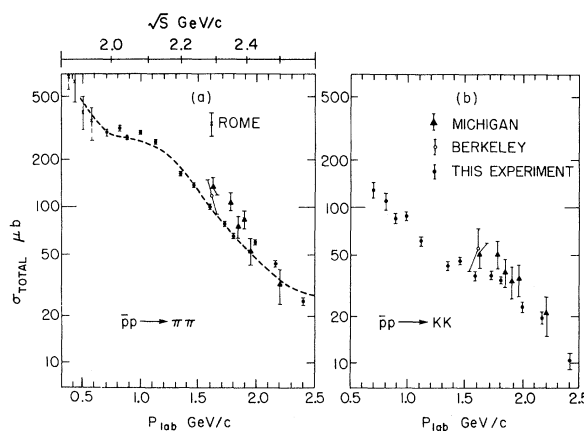

FIG. 2. Total cross sections for $\bar{p}p\to\pi^+\pi^-$ and $\bar{p}p\to K^+K^-$ from this and other experiments. The Michigan data are contained in Ref. 6, and the remaining points are listed in Ref. 7. The dashed curve in (a) is the resonance fit discussed in the text.

of states below 1.0 GeV/c and another set of states above 1.7 GeV/c with interference in between. The fall of the a_2 and a_4 coefficients, the negative dip in the a_6 coefficient, and the peak in the a_8 coefficient also reflect this picture. Therefore we have attempted to fit the two-pion folded cross section with two direct-channel resonances and constant backgrounds. Charge-conjugation and parity invariance permit only the triplet $\bar{p}p$ states with $L=J\pm 1$ to couple to a two-pion state of angular momentum J. The differential cross section in this case is given by[9]

$$\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\left\{\left|\sum_J\left[\left(\frac{A_J}{\epsilon_J-i}+A_J'\right)\left(\frac{J+1}{2J-1}\right)^{1/2}+\left(\frac{B_J}{\epsilon_J-i}+B_J'\right)\left(\frac{J}{2J+3}\right)^{1/2}\right]Y_J^1\right|^2+\left|\sum_J\left[\left(\frac{A_J}{\epsilon_J-i}+A_J'\right)\left(\frac{J}{2J-1}\right)^{1/2}-\left(\frac{B_J}{\epsilon_J-i}+B_J'\right)\left(\frac{J+1}{2J+3}\right)^{1/2}\right]Y_J^0\right|^2\right\},\quad(2)$$

where the A_J and B_J are real numbers which describe the partial widths from the initial states with orbital angular momentum $J-1$ and $J+1$, respectively, to the meson resonances of spin J. The masses (m_{RJ}) and widths (Γ_J) of the resonances are contained in the ϵ_J, where $\epsilon_J=(m_{RJ}^2-s)/m_{RJ}\Gamma_J$ with s equal to the square of the total center-of-mass energy.[10] A_J' and B_J' are the constant complex background terms.

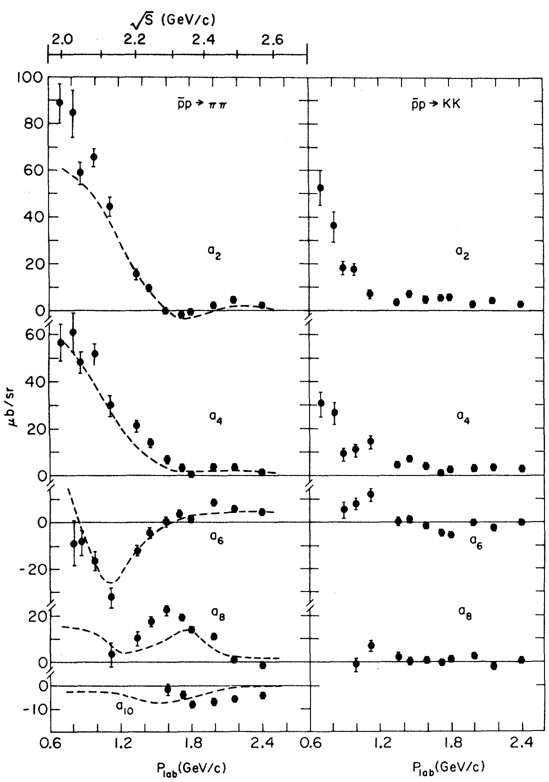

FIG. 3. Legendre coefficients from fits to the folded differential cross sections. The error bars are calculated from the diagonal elements of the error matrix. Some of the higher coefficients at the lower momenta are not statistically significant but are included for completeness. The dashed curves in the $\pi\pi$ case are the resonance fit discussed in the text.

We attempted to fit the folded cross-section data with the above expression. A least-squares minimization program was used and we found that, for a variety of trial starting conditions, the main contribution to the data came from a $J=3$ and a $J=5$ state. This result, surprising at first in view of the peak in the a_8 coefficient, is due to the fact that the spherical harmonics Y_3^1 and Y_5^1 can interfere to give a term similar to $|Y_4^0|^2$ without the strong peaking near $|\cos\theta_{c.m.}|=1.0$ characteristic of this polynomial. To obtain a quantitatively acceptable fit we included background terms in the $J=1$, 2, and 3 partial waves.

The results of this fit are shown by the dashed curves in Figs. 2 and 3 and have been obtained with a $J=3$ resonance at $p_{lab}=1.12$ GeV/c ($m_R=2.12$ GeV, $\Gamma=0.249$ GeV), and a $J=5$ resonance at $p_{lab}=1.60$ GeV/c ($m_R=2.29$ GeV, $\Gamma=0.165$ GeV). Since these resonances decay into two pions, it follows that $I=1$, $P=-1$, and $G=+1$. Fits using more complicated forms for the elements of the scattering matrix given by Eq. (2) are presently under investigation.[11]

It is also important to note that our fit is only to the folded distributions. In the following paper (see Fig. 2) we present and discuss the results from the annihilations in the forward-backward region, $|\cos\theta_{c.m.}|\geq 0.96$, for which we could identify the charge state of each meson.[12] These data show no evidence for resonance formation except for a shoulder at 1.8 GeV/c in the $\bar{p}p\to\pi^+\pi^-$ channel. Between 0.7 and 1.9 GeV/c the forward-backward asymmetry oscillates but is never greater than a factor of 2 indicating the dominance of states of the same parity. However, above and below this momentum range the forward-backward asymmetry is very large, as can be seen from our experiment and the data of Bizzari et al.[8] It is therefore clear that a complete fit to the reaction $\bar{p}p \to \pi^+\pi^-$ must eventually reproduce this asymmetry.

The channel $\bar{p}p \to K^+K^-$ exhibits Legendre coefficients which are similar to those of the $\bar{p}p \to \pi^+\pi^-$ below 1 GeV/c but not at higher momenta.[13] The total cross sections for both the $\pi^+\pi^-$ and K^+K^- channels are shown in Fig. 2 and can be fitted with straight lines depending on energy as $s^{-6.3}$ for $\pi^+\pi^-$ and $s^{-4.6}$ for K^+K^-. Nevertheless the $\pi^+\pi^-$ total cross section does manifest shoulders near p_{lab} 1.0 and 2.0 GeV/c which may be associated with the above-mentioned resonances.

Boson resonances in this energy region have been reported by the CERN missing-mass spectrometer group[14]; they are the T and U resonances with widths less than 0.015 and 0.024 GeV, respectively. While our data do indicate that these resonances couple very weakly to this $\bar{p}p$ channel, it is possible that our energy resolution is too coarse to reveal their presence.[15]

Similarly, enhancements have been observed in $\bar{p}p$ total cross sections by Abrams et al.[16] Two enhancements are found in the $I = 1$ channel at $M = 2.190$ GeV, $\Gamma = 0.085$ GeV, and $M = 2.345$ GeV, $\Gamma = 0.140$ GeV. The position of these resonances is within 0.070 GeV from our mass determination but the width of the lower resonance is significantly larger in our case. Nevertheless, in view of the uncertainties involved in such determinations for both experiments, further analysis is needed to establish a connection between these two results.

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[1]D. Fong, thesis, California Institute of Technology, 1968 (unpublished); D. Fong et al., to be published.

[2]The values of these differential cross sections in both graphical and tabular form at all the momenta are contained in California Institute of Technology Report No. CALT-68-197 (unpublished).

[3]J. K. Yoh et al., Phys. Rev. Letters 23, 506 (1969).

[4]We are grateful to Dr. B. Leontić and collaborators for the loan of this counter.

[5]A. S. Carroll et al., Phys. Rev. Letters 21, 1282 (1968).

[6]J. W. Chapman et al., Phys. Rev. Letters 21, 1718 (1968).

[7]G. Lynch et al., Phys. Rev. 131, 1287 (1963).

[8]R. Bizzari et al., Istituto di Fisica dell'Università di Roma, Nota Interna No. 213, 1969 (unpublished).

[9]J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. 24, 258 (1952).

[10]J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[11]In particular, using the dipole resonance model of C. Rebbi and R. Slansky (Phys. Rev., to be published), we are able to obtain a better fit with a $J = 5$ monopole resonance of $m_R = 2.43$ and $\Gamma = 0.271$ GeV, and $J = 3$ dipole resonance of $m_R = 2.13$ GeV and $\Gamma = 0.46$ GeV.

[12]B. Barish et al., following Letter [Phys. Rev. Letters 23, 607 (1969)].

[13]At present we have not attempted to fit the K^+K^- distributions with a resonance model.

[14]M. N. Focacci et al., Phys. Rev. Letters 17, 890 (1966).

[15]The effect of such heavy boson resonances has not manifested itself in the backward elastic $\bar{p}p$ channel either (see Ref. 3). An argument is presented in Ref. 3 justifying the possible lack of excitation of the leading boson Regge trajectory in $\bar{p}p$ interactions.

[16]R. J. Abrams et al., Phys. Rev. Letters 18, 1209 (1967).