CROSS SECTIONS FOR THE REACTIONS $\bar{p}p \to \pi^+\pi^-$ AND K^+K^- NEAR 2 GeV/c*

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The differential and total cross sections for the reactions $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ have been measured at six laboratory momenta, ranging from 1.62 to 2.20 GeV/c. The $\pi^+\pi^-$ cross section falls from (137 ± 16) to (32 ± 8) μb over this interval while the K^+K^- cross section falls from (51 ± 10) to (21 ± 6) μb. The center-of-mass angular distributions for the two channels differ remarkably.

We have measured the differential and total cross sections for the reactions $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ at six laboratory momenta between 1.6 and 2.2 GeV/c. The $\pi^+\pi^-$ cross section is found to be decreasing smoothly and very rapidly with increasing energy, falling off as $S^{-(8.6\pm1.3)}$, where S is the square of the center-of-mass energy. The angular distribution shows no evidence of the forward or backward peaking expected if the reaction were dominated by baryon exchange. Its structure suggests instead that the $\pi^+\pi^-$ final state results largely from one or more direct-channel resonances of high spin.

The K^+K^- angular distribution, on the other hand, is peaked strongly forward (i.e., the K^- tends to go in the same direction as the incident antiproton) and thus may be dominated by hyperon exchange. Then comparison of the K^+K^- cross section with that for $\bar{p}p \to K^0\bar{K}^0$ obtained from the same exposure indicates that $I=0$ hyperon exchange dominates $I=1$ hyperon exchange. The total cross section for K^+K^- production decreases as $S^{-(5\pm2)}$.

The data were obtained from 150 000 photographs of antiproton interactions in the Midwest Universities Research Association–Argonne 30-in. hydrogen bubble chamber with an average of 13 antiprotons per picture. Candidates for $\pi^+\pi^-$ and K^+K^- events came from two different double scannings of the film. The first scanning was designed to select candidates for high-momentum-transfer elastic scatters,[1] and accepted approximately 40% of all pion or kaon pairs. A second set of scanning rules was designed to find the remainder of the meson pairs, namely those in which the projected opening angle between the two outgoing tracks was greater than 90°. A computer program was written to generate various possible kinematic configurations and spatial orientations of annihilations into pion and kaon pairs and to project the tracks onto the film. The program then verified that all such events would pass either or both sets of rules.

The film was scanned twice with each set of rules. The combined scanning efficiency (based on events which had a four-constraint fit to a pion or kaon pair) was (99 ± 1)% for events with $|\cos\theta_{\text{c.m.}}| \le 0.9$, where $\theta_{\text{c.m.}}$ is the center-of-mass angle of the π^- or K^- with respect to the incident $\bar{p}$. A more thorough study was undertaken of the region $|\cos\theta_{\text{c.m.}}| > 0.9$ because of the known tendency for scanning personnel to overlook events in which both outgoing tracks are nearly parallel with the beam track. The study included a special scanning of $\frac{1}{6}$ of the film with rules designed to discover only events with $|\cos\theta_{\text{c.m.}}| \ge 0.96$. In addition to real meson-pair events, events which fit the final states $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$ with a slow π^0 were used because they were indistinguishable from real meson pairs at the scanning table. The result was that the scanning efficiency fell from (99 ± 1)% at $|\cos\theta_{\text{c.m.}}| = 0.90$ to (70 ± 10)% in the interval $0.965 \le |\cos\theta_{\text{c.m.}}| \le 0.985$. This efficiency was the same for both K pairs and π pairs and for positive or negative $\cos\theta_{\text{c.m.}}$, within the quoted errors. Beyond $|\cos\theta_{\text{c.m.}}| = 0.985$, there were too few events to evaluate a scanning efficiency. Therefore, we carry out our analysis of the data only in the region $|\cos\theta_{\text{c.m.}}| \le 0.985$.

Lastly, it was verified that the orientation of the production plane of the events in the bubble chamber was randomly distributed, as it should be if there were no scanning bias against particular orientations. Statistical uncertainty in the randomness of the observed distribution and uncertainty in the scanning efficiency introduce a 5% systematic uncertainty in the total cross sections.

Approximately 22 000 events were measured and processed by the geometrical reconstruction and kinematic constraint programs CAST-TVGP-SQUAW. All events which failed the geometry program were remeasured.

Of the events measured, 223 fit the four-constraint hypothesis $\bar{p}p \to \pi^+\pi^-$ with $\chi^2 < 13.3$ (1% con-

Table I. Cross sections (σ) and numbers of events observed (N) for the reactions $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$. S is the square of the center-of-mass total energy. The errors are statistical errors only.

Pbeam	S	$\bar{p}p \to \pi^+\pi^-$		$\bar{p}p \to K^+K^-$	
		σ		σ	
(GeV/c)	(GeV^2)	μb	N	μb	N
1.62	5.272	137 ± 16	72	51 ± 10	25
1.77	5.522	109 ± 14	62	51 ± 10	27
1.83	5.617	76 ± 12	44	39 ± 8	21
1.89	5.717	84 ± 11	60	34 ± 8	22
1.95	5.818	53 ± 10	32	35 ± 8	19
2.20	6.250	32 ± 8	18	21 ± 6	11

fidence level) and had no alternative hypothesis which fit. The χ^2 probability, or confidence-level, distribution for these events was flat. Another 18 events with χ^2 between 13.3 and 33 were accepted as pion pairs because no other hypothesis fit; furthermore, the unconstrained missing mass and energy for these events were consistent with zero in all but five cases. There were 48 events with both a fit ($\chi^2 < 33$) to the four-constraint hypothesis, and a fit ($\chi^2 < 6.6$) to the one-constraint hypothesis, $\bar{p}p \to \pi^+\pi^-\pi^0$. A study of the confidence-level distributions for both hypotheses and of the missing-mass distribution for the events proved to our satisfaction that only 9 ± 4 of these events had three-pion final states. Thus the total number of pion pairs found was 289 with an unremovable background of $(3 \pm 1.5)\%$.

Only 38 events fit the four-constraint hypothesis $\bar{p}p \to K^+K^-$ unambiguously. There were an additional 80 events which were ambiguous with the hypothesis $\bar{p}p \to \pi^+\pi^-\pi^0$. Of these, 18 could be resolved by measuring the ionization of one of the outgoing tracks. None of these events proved to be pion events. A study of the confidence-level distributions and missing-mass distributions of the remaining 62 events indicated that most probably none, and at most 10, of these events were actually pion events. Only 9 of the K^+K^- events also fit the one-constraint hypothesis $\bar{p}p \to K^+K^-\pi^0$. From studies analogous to those made for the $\pi^+\pi^-$ sample, we believe that all of these nine events are K^+K^- events. Thus 127 kaon pairs were found.

The resulting cross sections are tabulated in Table I and displayed along with other published cross sections[2-5] in Fig. 1. The errors shown are statistical errors only. There is an additional $\pm 8\%$ systematic error arising from the uncertainty in the background subtraction and the nor-

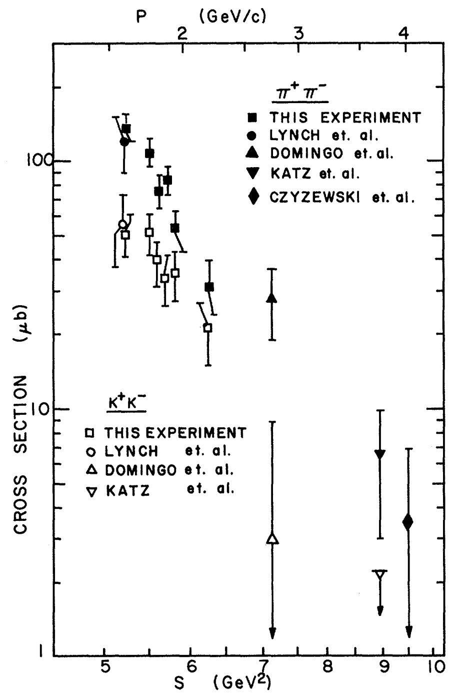

FIG. 1. Total cross sections for the reactions $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ as a function of S, the square of the total center-of-mass energy (lower scale) or laboratory momentum (upper scale).

malization. The center-of-mass angular distributions are shown in Fig. 2.

The following features of the data are noteworthy. The $\pi^+\pi^-$ cross section in our experiment decreases much more rapidly with increasing energy than the K^+K^- cross section. At the highest momentum (2.2 GeV/c) the $\pi^+\pi^-$ cross section is only 1.5 times larger than the K^+K^- cross section. By way of contrast, the average cross section for the reaction $\bar{p}p \to K^0\bar{K}^0$ measured in the same film is only (5.5 ± 2) μb, or six times smaller than the K^+K^- cross section.[6]

The angular distributions for the two final states are markedly different. The K^+K^- angular distribution is peaked forward whereas the $\pi^+\pi^-$ angular distribution is fore-aft symmetric with a structure suggesting minima near $\cos\theta_{\mathrm{c.m.}} = \pm 0.3$ and ± 0.9 and maxima near $\cos\theta_{\mathrm{c.m.}} = 0$ and ± 0.6.

A consistent, but not necessarily unique, interpretation of these data is as follows. Annihilation into K pairs proceeds mainly through the exchange of hyperons. The absence of a backward peak is readily understandable because of the absence of any known hyperon of strangeness +1 and charge +2. We note that the energy dependence of this reaction (S^{-5}) is the same as that for the

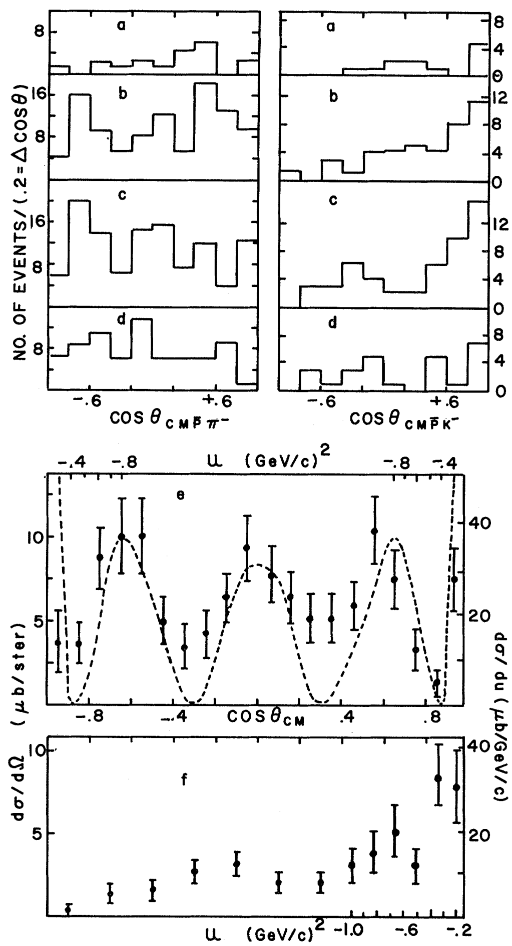

FIG. 2. (a)-(d) Angular distribution for the reactions $\bar{p}p\to\pi^+\pi^-$ (left-hand column) and $\bar{p}p\to K^+K^-$ (right-hand column) as a function of the center-of-mass angle between the incident antiproton and outgoing negative track, in the limits $-0.985<\cos\theta_{\text{c.m.}}<0.985$. (a) Data at $P_{\text{beam}}=2.2$ GeV/c; (b) at 1.89 and 1.95 GeV/c; (c) at 1.77 and 1.83 GeV/c; (d) at 1.62 GeV/c. (e) Differential cross section for $\bar{p}p\to\pi^+\pi^-$ based on the sum of the data in (a) through (d). u is the approximate four-momentum transfer from the $\bar{p}$ to the forward-going particle. It is approximate because u depends on both $\cos\theta_{\text{c.m.}}$ and the center-of-mass energy. The curve is the spherical harmonic $|Y_4^0|^2$. (f) Differential cross section for $\bar{p}p\to K^+K^-$ based on the sum of the data in (a) through (d).

reaction $\pi^-p\to\Sigma^-K^+$, which also appears to be dominated by hyperon exchange.[7] The backward peak in K^+p elastic scattering may also be due to hyperon exchange.[8,9] If we compare $d\sigma/du$ for backward K^+p scattering and for annihilation into K^+K^-, at $u=-0.2$ to -0.4 and at the same S value, we find the former is two times larger. (u is the four-momentum transfer from the proton to the K^+, or the antiproton to the K^-, respectively.)

Our small value of $\frac{1}{6}$ for the ratio of annihilations into neutral and into charged kaon pairs indicates that the $I=0$ hyperon exchange dominates over the $I=1$ exchange, since pure $I=1$ exchange would give a ratio of 4. This is consistent with other evidence that the $N\Sigma K$ coupling constant is much smaller than the $N\Lambda K$ coupling constant (see Kim[10]).

The $\pi^+\pi^-$ final state might have been similarly dominated by the exchange of neutrons and of $N^{*++}(1238)$ (or the Regge trajectories containing these particles), which would lead to both forward and backward peaking of the angular distribution. Barger and Cline[11] have made quantitative predictions based on such a model for energies somewhat higher than ours. The absence of such peaking suggests that direct-channel resonances are the major contributions to this cross section at our energies. The structure which we observe in the angular distribution would then imply that rather high-spin resonances are involved. The angular distribution fits the spherical harmonic Y_4^0 (plus a small amount of flat background) remarkably well [see Fig. 2(e)], except for the absence of large peaks at $\cos\theta=\pm1$. We do not believe that a scanning bias can be responsible for the absence of such peaks. No other combination of the two spherical harmonics Y_J^0 and Y_J^1 (i.e., $a|Y_J^0|^2+b|Y_J^1|^2$) closely resembles the data. We can conclude only that we are not observing a pure state. The structure which is observed could be the result of a dominant $J=4$ state plus a background (for instance, an exchange process) whose only effect is to cancel the backward peak, but could also be the accidental result of a much more complicated mixture of states having nothing to do with $J=4$. The situation will hopefully be clarified by several experiments in progress[12] in the region 1.0-1.6 GeV/c (laboratory momentum).

If we are seeing the effects of a $J=4$ $\pi\pi$ resonance, then its quantum numbers $J^PI^G=4^+0^+$. Such a state could be the Regge recurrence of the f^0, which would be expected to occur near our mass region. The monotonic decrease of our total cross section indicates that we could be on the high-energy edge of such a resonance. The backward peak which we see in $\bar{p}p$ elastic scattering from the same exposure[1] could also be due to such a resonance.

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[1]J. Lys, J. Chapman, D. Falconer, C. T. Murphy, and J. C. Vander Velde, Phys. Rev. Letters 21, 1116 (1968).

[2]V. Domingo, G. P. Fisher, L. Marshall Libby, and R. Sears, Phys. Letters 25B, 486 (1967).

[3]W. M. Katz, B. Forman, and T. Ferbel, Phys. Rev. Letters 19, 265 (1967).

[4]O. Czyzewski, B. Escoubes, Y. Goldschmidt-Clermont, M. Guinea-Moorhead, T. Hofmokl, R. Lewisch, D. R. O. Morrison, M. Schneeberger, and S. de Unamuno, in the Proceedings of the Sienna International Conference on Elementary Particles (Societá Italiana de Fisica, Bologna, Italy, 1963), Vol. 1, p. 271.

[5]G. Lynch, P. Eberhard, G. Kalbfleisch, J. Lannutti, B. Maglić, J. Shafer, M. L. Stevenson, and N. Xuong, Phys. Rev. 131, 1287 (1963).

[6]T. M. Church et al., "Hyperon Production in $\bar{p}p$ Collisions Near 2 GeV/c," to be published.

[7]O. Dahl, L. Hardy, R. Hess, J. Kirz, D. Miller, and J. Schwartz, Phys. Rev. 163, 1430 (1967).

[8]D. Cline, C. Moore, and D. Reeder, Phys. Rev. Letters 19, 675 (1967).

[9]A. S. Carroll, J. Fischer, A. Lundby, R. H. Phillips, C. L. Wang, F. Lobkowicz, A. C. Melissinos, Y. Nagashima, C. A. Smith, and S. Tewksbury, Phys. Rev. Letters 21, 1282 (1968).

[10]J. K. Kim, Phys. Rev. Letters 19, 1079 (1967).

[11]V. Barger and D. Cline, Phys. Letters 25B, 415 (1967).

[12]Comparison of our data with the preliminary results of these other experiments and speculations on the possible existence of a resonance in the system may be found in C. T. Murphy, Argonne National Laboratory Report No. ANL/HEP 6812 (unpublished). Complete details pertaining to the analysis of this experiment are available in Michigan Bubble Chamber Research Note 81/68.

DIRECT EVIDENCE FOR THE MULTIPLET ASSIGNMENTS OF $\Lambda(1520)$ AND $\Lambda(1405)$†

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A measurement has been made of the relative signs of the resonant $K^-p \to \Sigma\pi$ reaction amplitudes coming from partial waves corresponding to $\Sigma(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$. From this it is shown that $\Lambda(1405)$ and $\Lambda(1520)$ are to be described as predominantly SU(3) singlets.

One of the triumphs of SU(3) has been the consistently correct prediction of the relative signs of resonant reaction amplitudes as derived from formation experiments. In particular, all the better established Y^* resonances formed in K^-p reactions and placed into singlets, octets, and decuplets according to mass formulas have correct relative signs between resonant amplitudes as measured in their $\Sigma\pi$ and $\Lambda\pi$ decay modes.[1,2] Breaking of SU(3) often alters the predicted decay rates considerably; however, unless it is severe, the relative signs are unaffected. In this Letter we investigate the interferences between the $J^P = \frac{3}{2}^+$ resonance $\Sigma(1385)$, the $J^P = \frac{1}{2}^-$ resonance $\Lambda(1405)$, and the $J^P = \frac{3}{2}^-$ resonance $\Lambda(1520)$ as measured in the reaction $K^-p \to \Sigma\pi$. Taking $\Sigma(1385)$ to be in a decuplet, we shall find that $\Lambda(1405)$ and $\Lambda(1520)$ are consistent with their conventional assignments as SU(3) singlets.

In this analysis we follow the procedure adopted by Watson, Ferro-Luzzi, and Tripp[3] of parametrizing the low-momentum K^-p coupled-channel amplitudes by constant complex scattering lengths and constant reaction phases, apart from the D_{03} amplitudes corresponding to $\Lambda(1520)$ which are written as Breit-Wigner resonances. All partial waves through $J = \frac{3}{2}$ are included.[4] The old experimental data[3] spanning the momentum region 250-513 MeV/c (c.m. energy 1470-1570 MeV) have been greatly augmented (about one-hundredfold at 390 MeV/c) by our more recent bubble-chamber experiment in the region 300-450 MeV/c. This partially completed experiment has so far yielded new angular distributions in the $\bar{K}^0n$,