their radiometric measurements at 3.2, 1.58, and 0.856 cm.

In conclusion, when compared with longer-wavelength measurements, the result reported here is eight standard deviations from that to be expected by a hot grey body or a simple λ^{-2} dependence of the background radiation. We believe this to constitute strong support for the radiometric results previously reported by BSW and the CN results of Bortolot, Clauser, and Thaddeus[4] in showing the spectral curvature appropriate to a 2.7-K blackbody. Finally, the average of our result and the previous measurements at 3.2, 1.58, 0.856,[11] and 0.33 cm[3] weighted inversely as their respective variances is 2.65 $\pm$0.09 K.

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[1]R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. 142, 414 (1965).
[2]A. A. Penzias, IEEE Trans. Microwave Theory Tech. 16, 608 (1968).
[3]P. E. Boynton, R. A. Stokes and D. T. Wilkinson, Phys. Rev. Lett. 21, 462 (1968).
[4]V. J. Bortolot, Jr., J. F. Clauser, and P. Thaddeus, Phys. Rev. Lett. 22, 307 (1969).
[5]K. Shivanandan, J. R. Houck, and M. Harwit, Phys. Rev. Lett. 21, 1460 (1968).
[6]J. R. Houck and M. Harwit, Astrophys. J. 157, L245 (1969).
[7]D. Muehlner and R. Weiss, Phys. Rev. Lett. 24, 742 (1970).
[8]D. T. Wilkinson, Phys. Rev. Lett. 19, 1195 (1967).
[9]W. A. Johnson, IEEE Trans. Microwave Theory Tech. 16, 621 (1968).
[10]F. I. Shimabukuro and E. E. Epstein, IEEE Trans. Antennas Propagat. 18, 485 (1970).
[11]R. A. Stokes, R. B. Partridge, and D. T. Wilkinson, Phys. Rev. Lett. 19, 1199 (1967).

$\bar{p}p$ Annihilation into $\pi^+\rho$ at Small Angles Between 1 and 2 GeV/c*

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We have studied the process $\bar{p}p$ into π^+X^- using wire spark chambers. The data cover the angular range of $\cos\theta_{\bar{p}\pi^+}{}^*$ between 0.96 and 1.0 at several incident momenta between 1 and 2 GeV/c. The reaction $\bar{p}p\to\pi^+\rho^-$ was observed with $(d\sigma/d\Omega)^*$ of the order of 100 μb/sr at several momenta.

A survey of two-charged-particle final states produced in antiproton-proton collisions has been performed between 1.0 and 2.1 GeV/c at approximately 0.1-GeV/c intervals. In addition to measuring the differential cross sections of $\bar{p}p$ annihilation into $\pi^+\pi^-$ or K^+K^-[1] and of $\bar{p}p$ backward scattering,[2] we have been able to measure the cross section for production of the quasi two-particle final state $\bar{p}p\to\pi^+\rho^-$ for the $\cos\theta_{\bar{p}\pi^+}{}^*$ range between 0.96 and 1.0. The average value of $\cos\theta_{\bar{p}\pi^+}{}^*$ is 0.99.

The experimental apparatus has been described in detail elsewhere.[2,3] A beam containing of the order of 10^3 $\bar{p}$'s per pulse was incident on a 14-in. liquid-hydrogen target. Counter hodoscopes were set to trigger on a forward-going positive particle. This forward-going particle was momentum analyzed by a magnet–wire-spark-chamber spectrometer and identified by a Cherenkov counter and a time-of-flight system as a pion, kaon, or proton.

Analysis procedure.—We have calculated the square of the missing mass (M_M^2) spectrum for events with forward pions in the M_M^2 range below 1.6 GeV^2. For M_M^2 above 1.6 GeV^2, the background from multipion processes is large and any enhancements in the M_M^2 spectrum as a result of the quasi two-particle processes are difficult to observe.

Figure 1(a) shows the M_M^2 spectrum for events at four different momenta. We extracted the number of $\pi^+\rho^-$ events using a least-squares fitting procedure. The $\pi^+\pi^-$ events give a line at a squared mass of 0.02 GeV^2 which we have broadened with a Gaussian resolution function of 0.05 GeV^2. A Breit-Wigner form was used to represent the $\pi^+\rho^-$ events, and the background was included in an incoherent quadratic form. Figure 1(b) shows a typical fit. The standard deviation of the Gaussian function was determined from a study of the resolution of our apparatus as revealed by the $\bar{p}p$ backward elastic events[2] and also by fitting the data at low incident momenta where the π signals are strong. Neither the mass nor the width of the π Gaussian affects the final number of ρ events N_ρ significantly. The number of π events obtained agrees with our previous $\bar{p}p\to\pi^+\pi^-$ data.[1]

For the ρ signal we assumed a Breit-Wigner form with mass M_ρ and width Γ_ρ, multiplied by a threshold cutoff factor η given by

$$\eta=[M_M^2-4M_\pi^2]^{3/2}/[A+(M_M^2-4M_\pi^2)^{3/2}]$$

$$\sim k^3/(A'+k^3),$$

where k is the π momentum in the ρ c.m. system. This factor is introduced to give the proper threshold factor k^{2L+1}. Variation in the constant

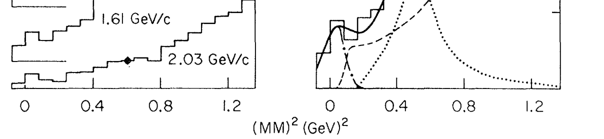

FIG. 1. (a) Raw M_M^2 spectrum for forward π^+'s at four momenta. The data are normalized so that equal area implies equal cross section. (b) Our fit to the M_M^2 spectrum. Note that the background is always concave.

A, set at 0.035 GeV^3, did not affect the fitted value of N_ρ. We used 720 MeV as the value of M_ρ since χ^2 minimizes sharply there. The result could well be due to the interference between ρ amplitude and a coherent background which we assume to be absent. However, the effect of the choice of M_ρ on N_ρ was very small (well within statistical error). On the other hand, χ^2 is relatively insensitive to Γ_ρ while N_ρ is almost linearly dependent on Γ_ρ. $\frac{1}{2}\Gamma_\rho$ was determined to be 0.104 ± 0.025 GeV by fitting at several momenta where the ρ signals are strong. This value of $\frac{1}{2}\Gamma_\rho$ was used at all other momenta where Γ_ρ could not be determined from χ^2 minimization. It is consistent with a value of 70 MeV for $\frac{1}{2}\Gamma$ obtained from hadron collisions folded with a resolution in M_M^2 of 0.05 GeV^2.[4] N_ρ changes by 25% when $\frac{1}{2}\Gamma_\rho$ changes by 0.025 GeV; this gives a lower limit to our systematic uncertainty.

No higher resonances were assumed although there are indications of structures (not statistically significant) in the A_1 and higher M_M^2 regions. We assumed that the smooth background could fit these structures. Investigation of fits including the A_1 resonance or using different ranges of M_M^2 showed that N_ρ is not affected significantly by those variations.

The quadratic background $A+BM_M^2+CM_M^4$ has a smooth lower cutoff at $M_M^2=(2M_\pi)^2$. It has been assumed that the background is *incoherent* with the ρ signal. It should be emphasized that the background underneath the ρ signal is always concave. If the actual background is linear, our results might be roughly 50% too high. We also investigated the fit with a cubic term DM_M^6 or with the linear term BM_M^2 removed. The results are the same within one standard deviation of the statistical error most of the time.

The acceptance of our apparatus was calculated using a Monte Carlo program. The errors quoted are statistical errors only. These are obtained from our fitting procedure and range between 15 and 50%. Systematic errors ($^{+30}_{-50}$%) are primarily due to the uncertainty in the determination of Γ_ρ and the shape of the background.

We have studied and applied the corrections to the normalization due to counter inefficiency (1%), wire-chamber inefficiency (0-5%), beam absorption (7-13%), event-reconstruction inefficiency (5%), and Cherenkov inefficiency in detecting pions (20%).[5]

Results and discussion.—Figure 2 shows the cross section at $\cos\theta_{\bar{p}\pi^+}{}^*=0.99$ for the process $\bar{p}p\to\pi^+\rho^-$, together with the cross section for $\bar{p}p$

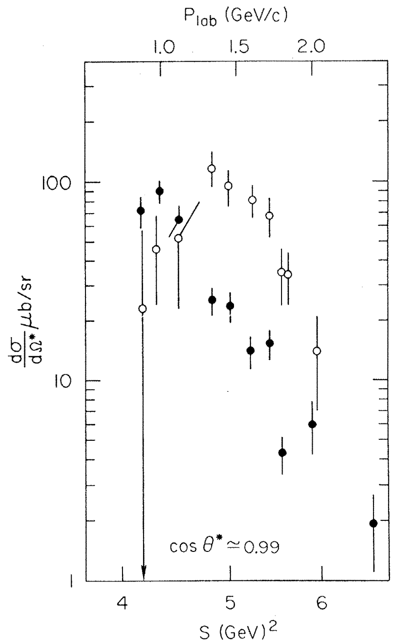

FIG. 2. $d\sigma/d\Omega$ for $\bar{p}p \rightarrow \pi^+\rho^-$ (open circles) and for $\bar{p}p \rightarrow \pi^+\pi^-$ (solid circles; see Ref. 1) at $\cos\theta_{\bar{p}\pi^+}{}^* = 0.99$ as a function of incident momentum.

$\rightarrow \pi^+\pi^-$ at the same angle obtained from our other experiment.[1] The cross section rises to a broad peak near $P_{lab} = 1.5$ GeV/c ($E_{c.m.} = 2.25$ GeV) and then drops sharply. This dependence can easily be observed in Fig. 1(a) where we show the raw $M_M{}^2$ spectrum. The data in Fig. 1(a) have been normalized so that they can be directly compared. The signal, clearly apparent at 1.34 and 1.61 GeV/c, is not very evident at 1.12 or 2.03 GeV/c. At the momenta below 1.12 GeV/c or above 2.03 GeV/c, the data are consistent with no ρ signal.

Although statistics are poor, we tried to extract some information on the angular dependence of the cross section. This is done by dividing the data into two bins with equal solid-angle acceptance.[6] The average $\cos\theta_{\bar{p}\pi^+}{}^*$ for the first bin is about 0.996 while it is about 0.975 for the second bin. The numbers of ρ events in both bins were found to be equal to within statistics except at 1.61 GeV/c, where the first bin had 283 ± 48 ρ events and the second bin had only 96 ± 37 ρ events. This backward peaking appears only at one momentum and thus we are not sure of its significance.

The broad peak in the cross section resembles that for $\bar{p}p$ backward scattering[2] and could suggest the possible existence of a resonance with negative G parity near 2.25 GeV which couples strongly to the $\bar{p}p$ channel. The width of the resonance appears to be rather broad—about 200 MeV. The peak covers the region of both T (2.198) and U (2.382) observed in the CERN missing mass experiment[7] and enhancements seen in the $\bar{p}p$ total cross-section measurement.[8] Taken together the broad plateau in our cross section might have been caused by more than one resonance.

We have compared our data with data on the reaction $\bar{p}p \rightarrow \pi^+\pi^-$. Experimentally, the cross sections for the $\pi^+\pi^-$ reaction in our energy region do not show any broad peak in contrast to the $\pi\rho$ data, as we see in Fig. 2. However if we combine our data with another experiment[9] at 8 GeV/c, we observe a similar high-energy decrease in the cross sections of both $\pi\rho$ and $\pi\pi$. Connecting the two sets of data, we see the energy dependence of the cross section go like s^{-3}-s^{-5}. The ratio R between the two reactions, i.e.,

$$R = \frac{d\sigma(\bar{p}p \rightarrow \pi^+\rho^-)/dt}{d\sigma(\bar{p}p \rightarrow \pi^+\pi^-)/dt},$$

is about 3 at $P_{lab} = 8$ GeV/c,[9] whereas it varies from 3 to 4 above $P_{lab} = 1.3$ GeV/c in our experiment. If the Regge-exchange mechanism dominates instead of the direct-channel resonances, it would give a somewhat less steep slope and the same values for the ratio,[10] because both reactions are dominated by the same trajectory (Δ^{++}). However the statements are obscured in view of the large errors involved in both experiments and the fact that our data are not at the high energies.

It is a pleasure to mention that Dr. R. H. Phillips of Brookhaven National Laboratory has participated actively during most phases of the experiment. We wish to acknowledge Mr. W. Atwood's contribution to the analysis. One of us (Y.N.) also wishes to thank Dr. F. Gilman for his helpful discussions.

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[1]B. C. Barish *et al.*, Phys. Rev. Lett. 23, 607 (1969); H. Nicholson *et al.*, Phys. Rev. Lett. 23, 603 (1969).

[2]J. K. Yoh *et al.*, Phys. Rev. Lett. 23, 506 (1969); J. K. Yoh, thesis, California Institute of Technology (unpublished).

[3]A. S. Carroll *et al.*, Phys. Rev. Lett. 21, 1282

(1968).

[4]Here the Breit-Wigner formula has been folded with the Gaussian resolution. If we combine the widths as Gaussians, we have $\frac{1}{2}\Gamma_\rho = [(0.07)^2 + (0.05/2\times0.72)^2]^{1/2} \simeq 0.078$. This value of $\frac{1}{2}\Gamma_\rho$ would reduce the cross sections by 25%. They are, however, with in the quoted errors.

[5]We use the Cherenkov counter to separate all protons and kaons from the forward particles. This is done at all momenta above 1.2 GeV/c. Comparison between results obtained from data with or without Cherenkov requirement shows good agreement.

[6]The solid angle of the two bins was equal to within 5%, as determined from the Monte Carlo calculation.

[7]M. N. Focacci *et al.*, Phys. Rev. Lett. 17, 890 (1966).

[8]R. J. Abrams *et al.*, Phys. Rev. Lett. 18, 1209 (1967).

[9]D. Birnbaum *et al.*, Phys. Rev. Lett. 23, 433 (1969). They give 1.9 ± 1.1 and $0.56\pm0.33\ \mu b/(\mathrm{GeV}/c)^2$, respectively, for $d\sigma(\bar{p}p\to\pi^+\rho^-)/dt$ and $d\sigma(\bar{p}p\to\pi^+\pi^-)/dt$ at $t\simeq-0.25\ \mathrm{GeV}^2$.

[10]$\mathrm{SU}(6)_W$ plus Δ^{++} exchange dominance gives $R=2$. See R. Carlitz and M. Kislinger, California Institute of Technology Report No. 68-237 (to be published).

Asymmetry Measurements for Elastic Scattering of K^+ Mesons by Polarized Protons*

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We report measured values of the asymmetry in the elastic scattering of K^+ mesons from polarized protons. The data were obtained at fourteen incident K^+ momenta from 1.33 to 2.58 GeV/c; the approximate angular range covered was $-0.85<\cos\theta_K^{\mathrm{c.m.}}<0.9$. We compare our results with other available measurements and note several significant differences.

In the past several years, the possible observations of $S=+1$ baryon states, Z^* particles, have focused attention on the K^+-nucleon interaction in the invariant-mass region below 2500 MeV.[1] That such states might exist was first suggested by resonance-like structures observed in the total cross section for K^+p scattering[2] and in K^- photoproduction from hydrogen.[3] More recently, phase-shift analyses using available data on K^+p total cross sections, differential elastic and inelastic cross sections, and asymmetries in elastic scattering from polarized protons have shown possible resonance behavior in the $P_{3/2}$ partial wave.[4,5]

We present new results of measurements of the asymmetry in the elastic scattering of K^+ mesons from polarized protons.[6] The data were obtained at 14 incident K^+ momenta between 1.33 and 2.58 GeV/c covering a typical angular range of $-0.85<\cos\theta_K^{\mathrm{c.m.}}<0.9$. These new asymmetry values constitute substantial additional data, particularly for K^+ momenta above 1.9 GeV/c where there were previously very few measurements. Because of the keen interest in the possible existence of exotic states and of the general usefulness of these data in future analyses, we are presenting these final experimental results without further interpretation. Our new measurements of differential cross sections, a phase-shift analysis, and fits to theoretical models will be reported later.

Most of the experimental apparatus shown in Fig. 1 has been described previously.[5,6] A separated beam of K^+ mesons with a central momentum determined to ±1% and a momentum spread

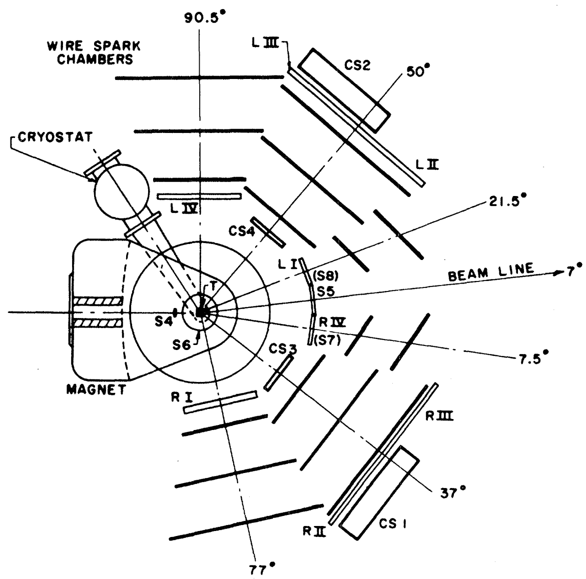

FIG. 1. Experimental arrangement for measurement of asymmetry in elastic scattering of $K^\pm$ mesons by polarized protons. Scintillation counters $S7$ and $S8$ are pairs of counters above and below the median plane.