the assertion made at the beginning of this Appendix. It is assumed that the qualitative observations which are made for 1.8-Gev incident protons are also valid for 5.7-Gev protons. That they may also be valid for about 0.5-Gev protons is suggested by the data of Kurchatov *et al.*[38] for the interactions of silver with 0.48-Gev protons; here, the smoothed log σ_A curves shows an over-all negative second derivative with respect to A which persists even while the σ_A decrease three orders of magnitude with decreasing A.

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[38] B. V. Kurchatov, V. N. Mekhedov, N. I. Borisova, M. Ya. Kuznetsova, L. N. Kurchatova, and L. V. Chistyakov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow,* July, 1955 (Akademiia Nauk, S.S.S.R., Moscow, 1955) [translation by Consultants Bureau, New York: Atomic Energy Commission Report TR-2435, 1956, p. 111].

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Polarization in π^--p Scattering between 500 and 940 Mev*

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A graphite-plate spark chamber has been used to analyze the polarization of protons recoiling from π^--p scattering. The observations were made at 90° (c.m. system) pion scattering angle for seven incident pion energies between 500 and 940 Mev, at 120° or 135° for five energies in this interval, and also at 75° for 500 Mev only. The results are compared with predictions of several models used to explain the maxima in the π^--p scattering cross section. Qualitative arguments show that the energy intervals between these maxima are not completely dominated by neighboring single-state resonances. Phase shifts found to be large in scattering also seem to be large in polarization.

I. INTRODUCTION

THE first maximum in the pion-nucleon scattering cross section occurs at about 200-Mev incident kinetic energy and is well understood in terms of a resonant state with even parity, $\frac{3}{2}$ units of total angular momentum J, and $\frac{3}{2}$ units of total isotopic spin T. Interpretations of the higher maxima are less certain.[1] The second peak, at 600 Mev, has been interpreted[2] as a resonance with $T=\frac{1}{2}$, $J=\frac{3}{2}$, and odd parity ($D_{\frac{3}{2}}$). The $T=\frac{1}{2}$ assignment is based on the relative behavior of the π^-p and π^+p total cross sections[3–5] and on the ratio of π^+/π^0 photoproduction.[6] The $J=\frac{3}{2}$ assignment is favored by photoproduction angular distributions.[7,8] The odd parity assignment[9] is largely supported by the observation of substantial polarization of the recoil protons in photoproduction[10,11] at energies intermediate between the first-two maxima. Quantitative analyses of the differential cross sections for π^-p scattering give evidence for a large D-wave contribution but do not establish a resonance.[12] The third maximum in the pion-nucleon cross sections at 900 Mev has been interpreted[1,2] as a $T=\frac{1}{2}$, $F_{\frac{5}{2}}$ resonance. However, on the basis of the observed structure in the π^+p total cross section near 900 Mev,[4,5] the π^-p scattering is probably affected by the $T=\frac{3}{2}$ as well as $T=\frac{1}{2}$ states at these energies.

Moravcsik[13] has described a qualitative scheme for using the polarization of recoil protons from π^-p elastic

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‡ Work done while on leave from the Rutherford High Energy Laboratory, Harwell, Didcot, Berks, England.

§ Supported in part by the U. S. Office of Naval Research.

[1] For a survey of elastic scattering data between 500 and 1000 Mev, see B. J. Moyer, Revs. Modern Phys. **33**, 367 (1961).

[2] R. F. Peierls, Phys. Rev. **118**, 325 (1960).

[3] H. C. Burrowes, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, R. A. Schluter, and M. A. Wahlig, Phys. Rev. Letters **2**, 119 (1959).

[4] J. C. Brisson, J. Detoef, P. Falk-Vairant, L. van Rossum, G. Valladas, and L. C. L. Yuan, Phys. Rev. Letters **3**, 561 (1959); Nuovo cimento **19**, 210 (1961).

[5] T. J. Devlin, B. C. Barish, W. N. Hess, V. Perez-Mendez, and J. Solomon, Phys. Rev. Letters **4**, 242 (1960).

[6] R. R. Wilson, Phys. Rev. **110**, 1212 (1958).

[7] F. P. Dixon and R. L. Walker, Phys. Rev. Letters **1**, 142, 458 (1958).

[8] J. I. Vette, Phys. Rev. **111**, 622 (1958).

[9] J. J. Sakurai, Phys. Rev. Letters **1**, 258 (1958).

[10] P. C. Stein, Phys. Rev. Letters **2**, 473 (1959).

[11] R. Querzoli, G. Salvini, and A. Silverman, Nuovo cimento **19**, 53 (1961).

[12] C. D. Wood, T. J. Devlin, J. A. Helland, M. J. Longo, B. J. Moyer, and V. Perez-Mendez, Phys. Rev. Letters **6**, 481 (1961).

[13] M. J. Moravcsik, Phys. Rev. **118**, 1615 (1960).

scattering at energies between the peaks to resolve the ambiguities. He shows that if two neighboring resonances dominate the energy region between them, the behavior of the polarization is qualitatively different for different assignments of the quantum numbers of the resonances.

In general, the polarization depends on a different combination of partial-wave amplitudes from that corresponding to the unpolarized differential cross section. It also involves interference between the spin-flip and non-spin-flip parts of the amplitudes, for which the incoherent sum only is obtained in angular distribution measurements. Even if the polarization data fail to resolve the ambiguities in a simple way, therefore, they can provide a considerable amount of additional information that must be satisfied by any model of the pion-nucleon interaction.

II. EXPERIMENTAL METHOD

Figure 1 is a diagram of the experimental arrangement used to study the reaction $\pi^- + p \rightarrow \pi^- + p$. The polarization of the recoil protons was measured by the asymmetry of their scatterings in carbon. A spark chamber with graphite plates was used as the analyzer because it had a large sensitive volume together with high angular resolution.

This spark chamber and its associated electronics are similar to those described by Beall *et al.*[14] The graphite plates were 1 in.×10 in.×11 in. but were hollow with $\frac{1}{8}$-in. wall thickness on the large-area sides. The outer surfaces were sprayed with silver paint and the plates were baked in a vacuum furnace. Up to three additional graphite slabs could be inserted into each plate through a slot in the edge to bring the carbon thickness up to almost one inch (4.1 g/cm^2). The plates were left hollow for the low-energy runs and were filled for the higher energies to increase the scattering probability of the proton. The spark chamber was filled with argon to one-atmosphere absolute pressure. The gap width was $\frac{1}{4}$ in.; a dc clearing voltage of the order of 50 v was applied across the gaps with polarity opposite that of the 20-kv pulsed voltage. The sensitive time of the chamber was less than one microsecond. A mirror system allowed the chamber to be viewed symmetrically from the side and bottom (90 deg stereo) through Lucite windows and photographed on a single 35-mm frame. Lucite cylindrical lenses mounted just outside the chamber windows with axes of curvature parallel to the plates enabled the camera at their mutual focus (75-in. focal length) to "see" into all the gaps and to be close enough to form a large image on the film. Figure 2 shows a typical chamber photograph.

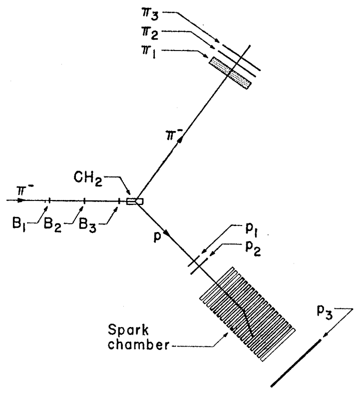

FIG. 1. Diagram of the experimental arrangement.

Negative particles from the Bevatron traversed the apparatus of another experiment[15] and were refocused to form the π^- beam shown in Fig. 1. The flux was approximately 10^4 pions per pulse of 0.25-sec duration. Defined by scintillation counters B$_1$, B$_2$, and B$_3$, the beam traversed a polyethylene (CH$_2$) target 1-in. wide by 8-in. high by 4-in. along the beam. The incident pion energy was varied between 500 and 940 Mev with an energy spread of approximately ±15 Mev including losses in the CH$_2$ target.

The scattered pion was detected by a telescope consisting of a water Čerenkov counter π_1, which would not respond to the recoil protons, followed by plastic scintillation counters π_2 and π_3. The recoil proton traversed scintillation counters P$_1$ and P$_2$ before entering the spark chamber. The logical requirement for triggering the spark chamber was a coincidence $B_1B_2B_3\pi_1\pi_2\pi_3P_1P_2$. At high incident energies, the protons had enough energy to penetrate through all the plates of the spark chamber, and the large counter P$_3$ was included in the coincidence requirement. The scattering angle and the solid angle were determined by the counter π_3, so that the angular interval was about ±7 deg in the center-of-mass (c.m.) system (c.m.s.). Although the spark chamber provided precise angular information, the amount of data was insufficient to permit a subdivision of this large angular interval.

The principal background in this experiment arose from quasielastic pion scattering in the carbon of the CH$_2$ target. This background was measured by a CH$_2$−C difference. A similar but smaller background arose from inelastic-scattering events in hydrogen, i.e., pion scattering with the production of an additional pion. An estimate of this background was made by comparing the average of the CH$_2$−C difference measured with the π^- telescope angle first smaller, then larger than the one corresponding to elastic scattering, with the CH$_2$ rate measured with the π^- telescope at the proper angle. These measurements were made at 700 and 900 Mev at 90 and 135 deg in the c.m.s., and straight lines were used to interpolate or extrapolate for other energies and angles. The effect of this background was small because in the analysis, range requirements consistent with kinematics for elastic scattering were imposed on the scattered protons.

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[14] E. F. Beall, B. Cork, P. G. Murphy, and W. A. Wenzel, Nuovo cimento **20**, 520 (1961); see also Rev. Sci. Instr. **32**, 480 (1961).

[15] O. Chamberlain, K. M. Crowe, D. Keefe, L. Kerth, A. Lemonick, T. Maung, and T. Zipf, Phys. Rev. **125**, 1696 (1962).

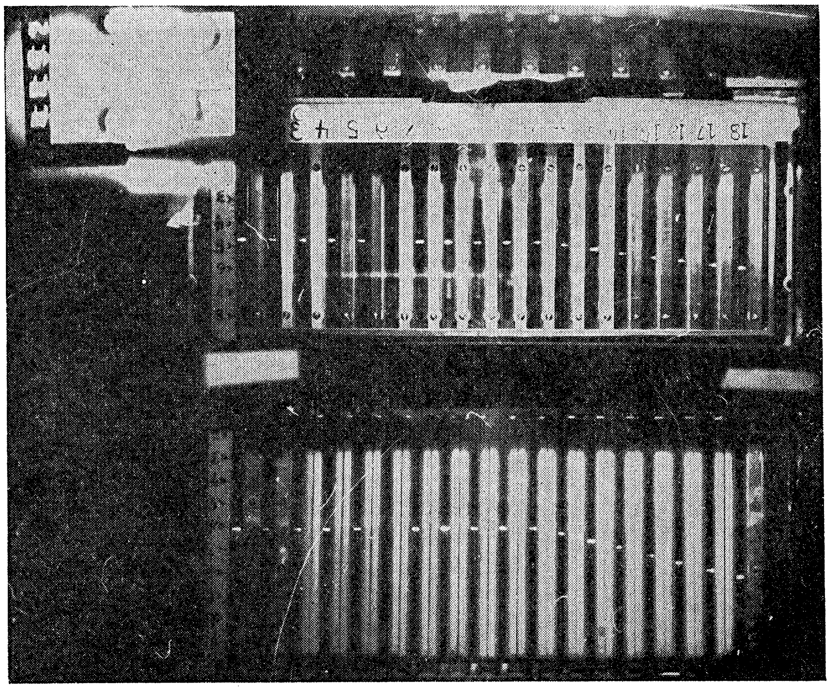

FIG. 2. Photograph of a scattered proton in the graphite spark chamber.

III. DATA ANALYSIS

The scanning and measurement of the photographs were very simple. The total time required was a few man months. For each of the two views, the proton-carbon scattering angle and sense, the number of gaps traversed by the proton before scattering, and the total number of gaps traversed were recorded. From this information and from the known range-energy relationship, the energy E, the scattering angle θ, and the azimuthal angle Φ, for the p-C scattering event, were obtained. In cases where the proton traversed the entire chamber, π-p kinematics and the energy loss prior to the p-C scattering were used to determine E. The analyzability $A(\theta,E)$ corresponding to p-C scattering was obtained from the graph by Birge and Fowler.[16] The analyzing power for each event is then given by $A(\theta,E)\cos\Phi$. The determination of $A(\theta,E)$ was limited by the finite thickness of the plates, and the error in $A(\theta,E)$ was typically 5 or 10%. Scattering angles less than 5 deg in the plane of the π-p scattering (the bottom view) or greater than Birge and Fowler's "elastic limit" were rejected. Sparks in at least two gaps after a scattering were required for measurement of the angle. No significant up-down asymmetry in the p-C scattering was found for the accepted protons. In the proton energy interval covered (60–550 Mev) and for those angles studied, the p-C polarization does not change sign. A predominance of scattering to the right in the chamber (e.g., the scattering shown schematically in Fig. 1) meant a downward,[17] or negative polarization. Here we have chosen the convention that the polarization is positive in the direction $\mathbf{K}_i\times\mathbf{K}_f$, where $\mathbf{K}_i$ and $\mathbf{K}_f$ are the initial and final pion momenta, respectively.[18]

The scattering data were analyzed by the maximum likelihood method. If P is the polarization of the recoil protons, the probability of observing a p-C scattering at energy and angles corresponding to $A\cos\Phi$ is proportional to $1+PA\cos\Phi$. The probability for a given P of obtaining the set of values of $A\cos\Phi$ which were actually observed is proportional to the product

$$\prod_{i=1}^{n}(1+PA_i\cos\Phi_i),$$

of all the individual probabilities. This product is a maximum for the most likely value of P. The statistical error is defined as the increment of P which lowers the product to $\exp(-1/2)$ of its maximum value.

The values of the uncorrected polarization P_{CH_2} (from CH_2) found in this manner are listed in Table I along with the number of events giving useful values of $A\cos\Phi$. Also listed are the fractional hydrogen inelastic contamination F_{in}, the carbon contamination F_{C}, and the corrected polarization P_{el}. The energy dependence of the corrected polarization is shown in Figs. 3 and 4.

The corrections were made in the following way. Let

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[16] R. T. Birge and W. B. Fowler, Phys. Rev. Letters **5**, 254 (1960).

[17] O. Chamberlain, Phys. Rev. **102**, 1659 (1956).

[18] This convention is the same as that of J. H. Foote, O. Chamberlain, E. H. Rogers, H. M. Steiner, C. E. Wiegand, and T. Ypsilantis, Phys. Rev. **122**, 948 (1961), but opposite to that of J. F. Kunze, T. A. Romanowski, J. Ashkin, and A. Burger, *ibid.* **117**, 859 (1960).

TABLE I. Observed and corrected polarization.

Incident π^- energy (Mev)	π^- scattering angle (c.m.s.)	No. of events	Uncorrected polarization P_{CH_2}	Fraction hydrogen inelastic contamination F_{in}	Fraction carbon contamination F_{C}	Corrected polarization P_{el}
500	90°	98	-0.47 ± 0.26	0.02 ± 0.05	0.18 ± 0.05	-0.55 ± 0.33
616	85°	169	$+0.09\pm0.16$	0.04 ± 0.05	0.22 ± 0.03	$+0.11\pm0.22$
695	90°	649	$+0.16\pm0.05$	0.06 ± 0.05	0.21 ± 0.03	$+0.19\pm0.09$
800	90°	163	$+0.13\pm0.14$	0.09 ± 0.05	0.23 ± 0.05	$+0.16\pm0.23$
830	90°	147	-0.28 ± 0.14	0.10 ± 0.05	0.27 ± 0.04	-0.37 ± 0.26
870	90°	88	-0.08 ± 0.18	0.11 ± 0.05	0.20 ± 0.03	-0.10 ± 0.28
940	90°	97	-0.58 ± 0.15	0.13 ± 0.05	0.30 ± 0.05	$-0.77_{-0.36}^{+0.33}$
500	75°	120	$-1.14_{-0.41}^{+0.46}$	0.02 ± 0.05	0.18 ± 0.05	$-1.36_{-0.53}^{+0.61}$
500	135°	135	-0.28 ± 0.17	0.15 ± 0.05	0.07 ± 0.01	-0.35 ± 0.27
616	135°	144	$-0.87_{-0.13}^{+0.14}$	0.15 ± 0.05	0.14 ± 0.02	-1.08 ± 0.27
667	120°	324	$+0.06\pm0.09$	0.18 ± 0.06	0.16 ± 0.08	$+0.08\pm0.23$
740	120°	126	$+0.52\pm0.17$	0.18 ± 0.06	0.21 ± 0.02	$+0.69\pm0.36$
912	120°	386	$+0.09\pm0.11$	0.15 ± 0.02	0.34 ± 0.03	$+0.11\pm0.30$

L and R represent scattering to the left and right, respectively, in the analyzer, and let the subscripts CH_2, in, and C indicate that the protons came from polyethylene, the hydrogen inelastic scattering, and the carbon in the target, respectively. Then the polarization P_{el} of protons recoiling from elastic π^--p scattering is

$$P_{\mathrm{el}}=[P_{\mathrm{CH}_2}-F_{\mathrm{in}}P_{\mathrm{in}}-F_{\mathrm{C}}P_{\mathrm{C}}]/[1-F_{\mathrm{in}}-F_{\mathrm{C}}],$$

where

$$F_{\mathrm{in}}=[L_{\mathrm{in}}+R_{\mathrm{in}}]/[L_{\mathrm{CH}_2}+R_{\mathrm{CH}_2}]$$

and

$$F_{\mathrm{C}}=[L_{\mathrm{C}}+R_{\mathrm{C}}]/[L_{\mathrm{CH}_2}+R_{\mathrm{CH}_2}].$$

The combined error in the measured polarization is

$$\Delta P_{\mathrm{el}}=\frac{1}{1-F_{\mathrm{in}}-F_{\mathrm{C}}}[(\Delta P_{\mathrm{CH}_2})^2+(F_{\mathrm{in}}\Delta P_{\mathrm{in}})^2+(F_{\mathrm{C}}\Delta P_{\mathrm{C}})^2$$
$$+(P_{\mathrm{el}}^2-P_{\mathrm{in}})^2\Delta F_{\mathrm{in}}^2+(P_{\mathrm{el}}-P_{\mathrm{C}})^2\Delta F_{\mathrm{C}}^2]^{\frac{1}{2}},$$

where ΔX indicates the error in X. Since we have no knowledge of P_{in}, let $P_{\mathrm{in}}=0$. If all values of P_{in} are equally likely (implying a flat probability distribution rather than Gaussian), then the probability for $P_{\mathrm{in}}>0.68$ is the same as the probability of exceeding one standard deviation in the case of a Gaussian distribution. We therefore take $\Delta P_{\mathrm{in}}=0.68$. The polarization in quasielastic p-p scattering by a carbon nucleus is found to be small for low energy protons[19] and to approach ordinary p-p polarization at 600 Mev.[20] The polarization in quasielastic π^--p scattering in the carbon nucleus may be expected to behave similarly. We therefore assume that P_{C} is given by

$$P_{\mathrm{C}}=(E_p/600)P_{\mathrm{el}}\left\{\begin{array}{l}+0.68P_{\mathrm{el}}[1-(E_p/600)]\\-0.68(E_p/600)P_{\mathrm{el}},\end{array}\right.$$

where E_p is the energy of the recoil proton. In assigning these errors, we assume that values of P_{C} on either side of $E_pP_{\mathrm{el}}/600$ are equally probable between zero and P_{el}, with zero probability outside these limits.

For the most part, as Table I shows, the corrections make only small changes between P_{CH_2} and P_{el}, and the errors are dominated by the statistics of the experiment and the magnitude of the factor $[1-F_{\mathrm{in}}-F_{\mathrm{C}}]^{-1}$.

In two cases the errors in the polarization given in Table I are not simply correlated with the numbers of events observed. For the 500-Mev 75-deg point, the proton energies were so low that the analyzing power of carbon (A cosΦ) was small, and each event has relatively less significance. Indeed, the result is dominated by the events with large values of A cosΦ. At high energies the contaminations were relatively large, and the polarization of recoil protons from π-C scattering is believed to

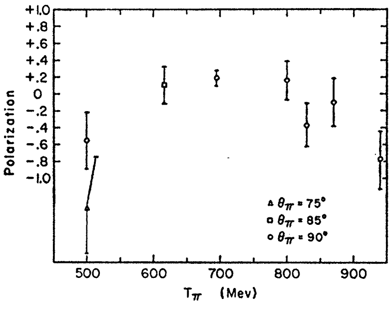

FIG. 3. Polarization at 90 deg (c.m.) vs pion kinetic energy.

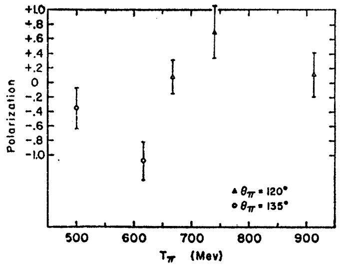

FIG. 4. Polarization at 120 deg (c.m.) and 135 deg (c.m.) vs pion kinetic energy.

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[19] R. Donaldson and H. Bradner, Phys. Rev. **99**, 892 (1955).

[20] M. G. Meshcheriakov, S. B. Nurushev, and G. D. Stoletov, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 361 (1956) [translation: Soviet Phys.—JETP **4**, 337 (1957)].

be large. These two effects increase the error at 912 Mev, where 386 events were measured.

IV. DISCUSSION OF RESULTS

The product $P(\theta)\sigma(\theta)$ of the polarization and the differential scattering cross section is proportional to the imaginary part of $f_\alpha^* f_\beta$, where f_α is the non-spin-flip amplitude and f_β is the spin-flip amplitude.

The expansion of this expression including all partial waves through F may be written[13]

$$P(\theta)\sigma(\theta)=\sin\theta(A+B\cos\theta+A'\cos^2\theta+B'\cos^3\theta+A''\cos^4\theta+B''\cos^5\theta), \quad (1)$$

$$\begin{aligned}
A&=A(SP,SF,DP,DF),\\
B&=B(SD,PP,PF,DD,FF),\\
A'&=A'(SF,PD,DF),\\
B'&=B'(PF,DD,FF),\\
A''&=A''(DF),\\
B''&=B''(FF),
\end{aligned}$$

where, for example, $A(SP)$ means that terms involving products of S-wave and P-wave amplitudes are included. We note that only products of amplitudes of states of opposite parity appear in the coefficients of even powers of $\cos\theta$. In the odd-power coefficients, these products occur between states of the same parity.

Since our polarization data include only a small amount of angular distribution information, it clearly is impossible to consider any general fit to the data. Therefore, in analyzing the data as a function of energy, we will take advantage of whatever characteristics of the interaction are indicated by the scattering experiments. For energies up to 600 Mev, for example, we assume with Wood *et al.*[12] that no states higher than D wave, $J=\frac{3}{2}$, contribute significantly. Then it is possible to expand (1) with relatively few terms. In this way we find that

$$\begin{aligned}
A&\propto \mathrm{Im}[(D_3^*-S_1^*)(P_3-P_1)],\\
B&\propto \mathrm{Im}[3S_1^*D_3+2P_3^*P_1-P_1^*P_3],\\
A'&\propto \mathrm{Im}[6P_3^*D_3-3P_3D_3^*]=\mathrm{Im}[9P_3^*D_3],\\
B'&=B''=A''=0,
\end{aligned} \quad (2)$$

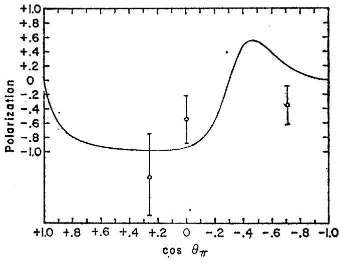

FIG. 5. Polarization at 500 Mev as a function of angle. The smooth curve is calculated from phase shifts obtained by interpolation from phase shifts at 430, 460, and 600 Mev given in reference 21.

In (2) we have used the notation on

$$D_3=a_{33}(D)/3+2a_{13}(D)/3,$$

where $a_{33}(D)$ and $a_{13}(D)$ are the $J=\frac{3}{2}$ D-wave amplitudes in the $T=\frac{3}{2}$ and $T=\frac{1}{2}$ states, respectively.

At 500 Mev, polarization measurements were made at three angles (Table I); so it is possible to solve for A, B, and A' simultaneously. We use for $\sigma(\theta)$ in (1) values obtained from extrapolation of the results of Wood *et al.*[12] In this way we find at 500 Mev:

$$\begin{aligned}
A/\sigma(90\text{ deg})&=P(90\text{ deg})=-0.55\pm0.33,\\
B/\sigma(90\text{ deg})&=-8.4\pm4.3,\\
A'/\sigma(90\text{ deg})&=-12.8\pm6.3.
\end{aligned} \quad (3)$$

The relatively large negative value for A' supports previous suggestions that P_3D_3 interference is important at energies just below the second resonance.[9] It also follows, however, that the P_3 and D_3 amplitudes do not completely dominate the π^--p interaction, because we would then expect from (2) that B is small and that $A'\approx-9A$; both predictions are in disagreement with (3). In fact, in order to account for the observed relative sign of A and A' as well as the magnitude of B, we require a significant S_1 or P_1 amplitude. The former is favored by the elastic scattering measurements.[12] Figure 5 shows the experimental values for the polarization at 500 Mev. The smooth curve is calculated from phase shifts obtained by interpolation from published phase shifts at 430, 460, and 600 Mev.[21]

The polarization values computed[22] from the 600-Mev phase shifts are shown in Fig. 6 with the present experimental results. Three curves by Franzini and Gaillard[23] are included in this figure. In two cases they assume a resonance in either the $D_{\frac{3}{2}}$ or $P_{\frac{3}{2}}$ state. The agreement of the experimental results with the "resonant" solutions does not, of course, prove that there is a resonance at 600 Mev but only that some phase shift (presumably that of the P_3 or D_3 amplitude) is large.

At energies above 600 Mev it is likely that the interaction may include up to F waves,[12] so that an effective analysis of the angular distribution of the polarization in terms of the present data is not feasible. Including the D_5 and F_5 amplitudes, the polarization at 90 deg is given by

$$P(90)=A/\sigma(90)=\mathrm{Im}[(D_3^*+3D_5^*/2-S_1^*)\times(P_3-P_1+3F_5/2)]. \quad (4)$$

If the second and third maxima are simple resonances, (4) implies a large value for A between the resonances if they are of opposite parities.[13] In this case the phase

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[21] W. D. Walker, J. Davis, and W. D. Shephard, Phys. Rev. **118**, 1612 (1960).

[22] We are indebted to R. Cence and other members of the Moyer group for computing these polarizations with their IBM-709 program, as well as for several illuminating discussions.

[23] P. Franzini and J.-M. Gaillard, Nuovo cimento **19**, 1062 (1961).

shift corresponding to the second maximum has presumably passed through 90 deg while that for the third maximum has not yet reached 90 deg, so that the difference in phase is sufficient to give a large value for A. Therefore the absence of a large negative value for A between the 600- and 900-Mev maxima (see Fig. 3) is evidence against simple resonance assignments of $D_{\frac{3}{2}}$ and $F_{\frac{5}{2}}$, respectively.

The negative value for P(90 deg) near the third maximum at 900 Mev is in qualitative agreement with Moravcsik's result for these assignments.[24] The $D_{\frac{3}{2}}$ phase shift presumably is still larger than the $F_{\frac{5}{2}}$ phase shift, so that the sine of the difference of these angles is negative in the expansion of (4). The large magnitude of the polarization is surprising at this distance from the $D_{\frac{3}{2}}$ peak, but large D and F interference at this energy is evident also in the differential cross sections.[1]

It is not surprising that there is difficulty in reconciling the polarization data with a simple two-resonance description of the second and third maxima in pion-nucleon scattering, for there is ample evidence in the total-cross-section and elastic-scattering measurements that the interaction is more complicated than this. Carruthers[25] has predicted the existence of a $T=\frac{3}{2}$, $D_{\frac{3}{2}}$ resonance between 850 and 950 Mev on the basis of the existence of a shoulder in the energy dependence of the π^+p total cross section together with the qualitative behavior of the π^-p charge-exchange cross section. Although the π^--p interaction is only one-third $T=\frac{3}{2}$, the presence of this resonance could account for the (90 deg) negative polarization at 940 Mev (Table I) through interference with the large F-wave amplitude found in the elastic scattering near this energy.[12]

The most successful way of accounting for the higher-energy maxima in pion-nucleon scattering has been in terms of isobar models.[26] At these energies there is the possibility of creating at least one extra pion in the final state; so that both the $T=\frac{3}{2}$, $J=\frac{3}{2}$ pion-nucleon, and the $T=1$, $J=1$[27] (and possibly other) pion-pion isobars are expected to play an important role in the interaction.[28,29]

Recently Peierls[30] has proposed that the second (600-Mev) maximum is due to the formation of a pion and an isobar $(\frac{3}{2},\frac{3}{2})$ which scatter in an intermediate state. The existence of a pole at the nucleon mass in the pion isobar scattering amplitude leads to an enhancement at 600 Mev. The third maximum (900 Mev) is then accounted for by a similar process with P-wave instead of S-wave pion-isobar coupling.

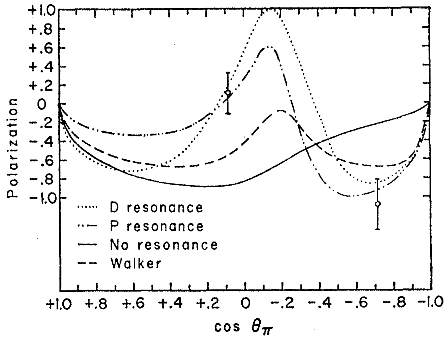

FIG. 6. Polarization at 600 Mev as a function of angle. Curves are for the 600-Mev phase shifts of reference 21, and for two resonant solutions and one nonresonant solution calculated in reference 23.

An alternative model by Ball and Frazer[31] attributes the second and third maxima to formation of a pion-pion $T=1$, $J=1$ isobar which is coupled to the nucleon in S wave or P wave, respectively. Both models give a $D_{\frac{3}{2}}$ state near 600 Mev, an $F_{\frac{5}{2}}$ state near 900 Mev, and also permit the $T=\frac{3}{2}$, $D_{\frac{3}{2}}$ state suggested by Carruthers.[25]

An interesting feature of the Ball-Frazer model[31] is that the maximum in the total cross section accompanies the rapid onset of an inelastic process, in this case, a pion isobar formation. The real part of the phase shift for a given state rises rapidly and then falls again as the inelastic cross section first rises and finally approaches total absorption for the state. The phase shift above the maximum then behaves quite differently from that which usually accompanies a resonance. We note that the absence of a large positive polarization in the region between the 600- and 900-Mev maxima is explained if the $D_{\frac{3}{2}}$ phase shift falls before the $F_{\frac{5}{2}}$ phase shift rises appreciably.

V. CONCLUSIONS

The data of the present experiment give only a crude survey of the behavior of the π^--p polarization as a function of energy in the region of the second and third maxima in the total cross section, but the results are inconsistent with the predictions of Moravcsik[13] based on the dominating influence of neighboring single-state resonances. On the other hand, it is apparent that a significant analysis will require considerably more detailed measurements of the angular distribution of the polarization at a number of energies in both isotopic spin states. At these energies inelastic processes are important, so that phase shifts are in general complex. In any case the number of states which are excited to a greater or lesser degree must be large, as can already be seen from the angular distribution[12] and photoproduction measurements.[7,8] Moreover, because of the simi-

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[24] We are indebted to William M. Layson, National Science Foundation predoctoral fellow now at CERN, Geneva, Switzerland, for correcting an error in our analysis of this result.

[25] P. Carruthers, Phys. Rev. Letters **6**, 303 (1960).

[26] See R. M. Sternheimer and S. J. Lindenbaum, Phys. Rev. **123**, 333 (1961) and references therein.

[27] W. R. Frazer and J. Fulco, Phys. Rev. Letters **2**, 365 (1959).

[28] P. Carruthers and H. A. Bethe, Phys. Rev. Letters **4**, 536 (1960).

[29] R. F. Peierls, Phys. Rev. Letters **5**, 166 (1960).

[30] R. F. Peierls, Phys. Rev. Letters **6**, 641 (1961).

[31] J. S. Ball and W. R. Frazer, Phys. Rev. Letters **7**, 204 (1961).

larity of many predictions of the pion-nucleon and the pion-pion isobar models, and because the effects of both isobars are probably present simultaneously, it may be necessary to concentrate on rather subtle experimental details. We note that the spark chamber is particularly well suited to polarization measurements, and as Moravcsik has pointed out,[13] polarization may be the best means of resolving ambiguities in angular momentum assignments even when the measurements are not very precise.

Note added in proof. The effect of inelastic processes on the recoil polarization in π^--p scattering has been investigated by P. B. Shaw [Phys. Rev. **124**, 1971 (1961)]. Moravcsik's results are not changed qualitatively, but the polarization magnitudes are slightly decreased in case the absorption is large. Our large positive value for the 740-Mev 120-deg polarization also disagrees with Shaw's result based on $D_{\frac{3}{2}}$ and $F_{\frac{5}{2}}$ resonance assignments for the 600- and 900-Mev maxima.

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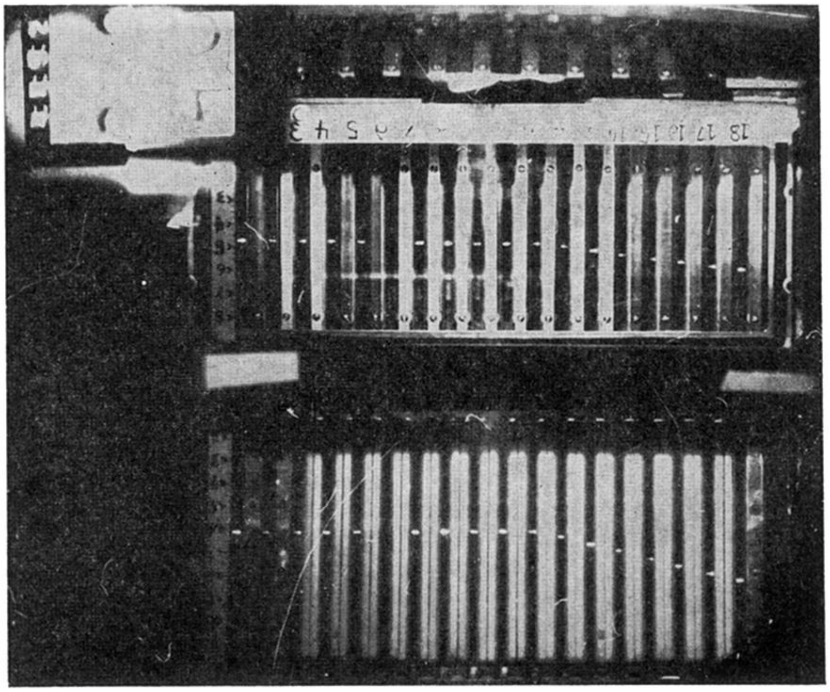

FIG. 2. Photograph of a scattered proton in the graphite spark chamber.