pair effects. We did not succeed and a reasonable hypothesis is that the contamination of pair production in our case was the order of 5% to 10%. I hope I understand your question?

MOZLEY: No, I meant even though you have eliminated the possibility of detecting any protons from π pair production, I thought that the existence of an alternative means of absorption of the gamma rays in this region would introduce imaginary parts to the matrix element components.

SALVINI: I believe you are in part right. We made our assumptions without speculating on the possible contents of *AB* and *BC*. We followed the phenomenological calculations of the type of Peierls. I am sure that we are not able yet to improve this situation and include the pair production detailed description.

PHOTOPRODUCTION OF POSITIVE PIONS FROM HYDROGEN

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I. INTRODUCTION

During the past year, work on the photoproduction of charged pions at " high energies " has consisted mainly of measurements on π^+ production from hydrogen at small angles. These measurements have been carried out at Cal. Tech. by Boyden and Walker, and at Frascati by Beneventano, Finocchiaro, Finzi, Mezzetti, Paoluzzi, and Schaerf. Both groups have used magnetic spectrometers to detect π^+ mesons produced in a liquid hydrogen target. The principal experimental difficulty at small angles is the presence of electrons which must be distinguished from the pions. The separation of pions and electrons is achieved by the use of two sets of counting criteria such that one is as efficient as possible in counting electrons and inefficient in counting pions, while the other set has the relative efficiencies reversed. If all the efficiencies are known, the separate counting rates of pions and electrons may be obtained. At Cal. Tech., electrons have been detected with efficiencies of 87% to 97% by showers produced in one or two lead convertors. From 6% to 15% of the pions simulate such showers under the conditions of counter biases used. The Frascati group has used two gas Čerenkov counters which are very efficient in counting electrons and are insensitive to pions. The measurements are continuing in both laboratories, and are being extended to higher energies, 1100 and 1200 MeV, by J. Kilner at Cal. Tech.

Measurements of π^+ photoproduction at small angles, less than 20° c.m., serve two purposes which are complementary. The first of these is to display effects of the " photoelectric term ", or interaction of the photon with the meson current, in the angular region where these effects are most easily recognizable. The second function of measurements at small angles is to provide a reliable extrapolation to 0°, where effects of the photoelectric term vanish, and where the theoretical interpretation of the data may consequently be simpler than at other angles. These features contribute to the general program of obtaining information about the pion-nucleon interaction.

II. DATA

The data obtained at various energies from 700 to 1100 MeV are shown in Figures 1 to 5. Older data [1)] at larger angles are also included. The cross section

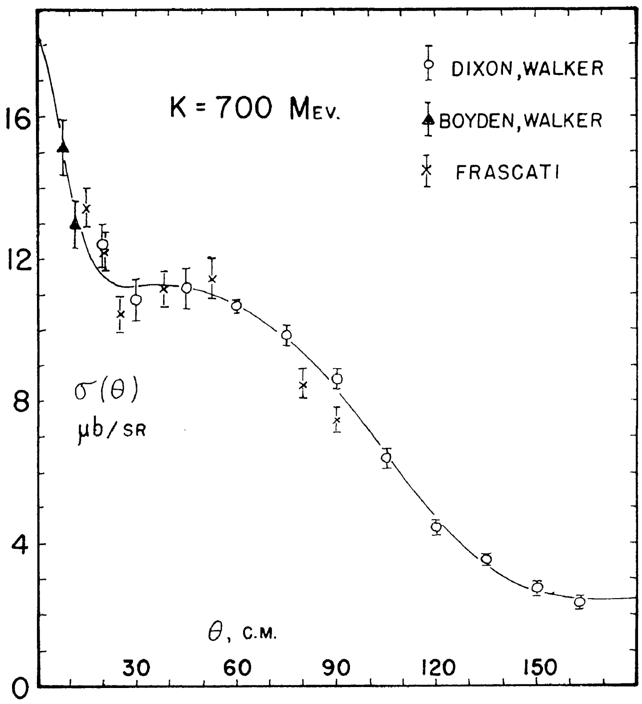

Fig. 1 Angular distribution in the c.m. system of π^+ from the reaction $\gamma+p\rightarrow\pi^++n$ for photon energy $k=700$ MeV. Preliminary data from Frascati (with an overall normalization factor) are compared to the Cal. Tech. data. The solid curve is a Moravcsik fit obtained by fitting $(1-\beta\cos\theta)^2\,\sigma(\theta)$ with a sixth order polynomial in $\cos\theta$. The curve has been fit to the Cal. Tech. data only.

rises steeply as the angle approaches 0° at all energies investigated. This rapid variation with angle presumably results from the photoelectric term interfering with other terms, and is characteristic of even the simplest theoretical cross section, calculated with the Born approximation, and illustrated for one energy in Fig. 6.

III. INTERPRETATION

Since no real theory exists at high energies, the hope of extracting information about the pion nucleon interaction from photoproduction data rests on the possibility of understanding the general features of the data in terms of a phenomenological theory involving photon multipoles and pion partial waves. Analyses of this sort have been made by a number of people, notably by Peierls[2]. In making the multipole analysis, it seems advantageous to separate the photoelectric term explicitly, since it contains many partial waves[3]. With this procedure, the photoproduction section at a given energy may be written as:

$$\sigma(\theta)=\tfrac{1}{2}\sum_s\left|b\frac{\sin\theta}{(1-\beta\cos\theta)}f_s(\theta)+\sum_{ij}\Big[E_{ij}f_{ij,s}(\theta)+M_{ij}g_{ij,s}(\theta)\Big]\right|^2$$

where the sum over s refers to the various combinations of initial and final nucleon spins. The first term, with coefficient b, is the photoelectric term which comes from the interaction of the photon with the

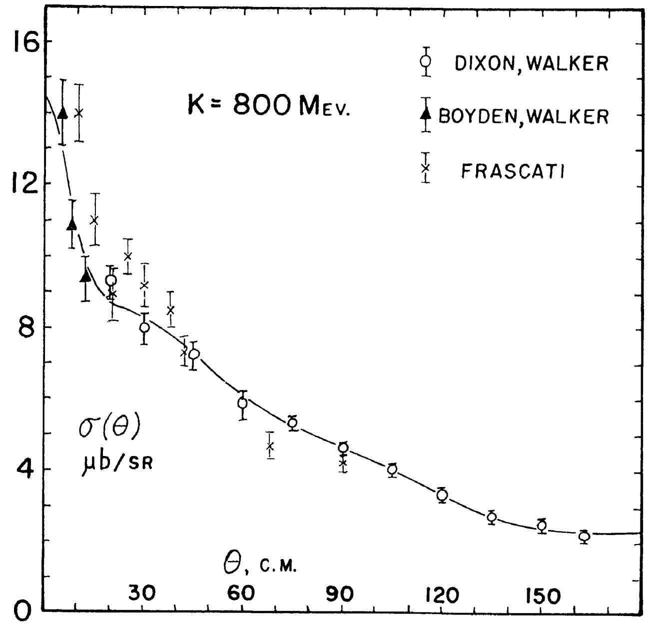

Fig. 2 Angular distribution at 800 MeV. See caption of Fig. 1.

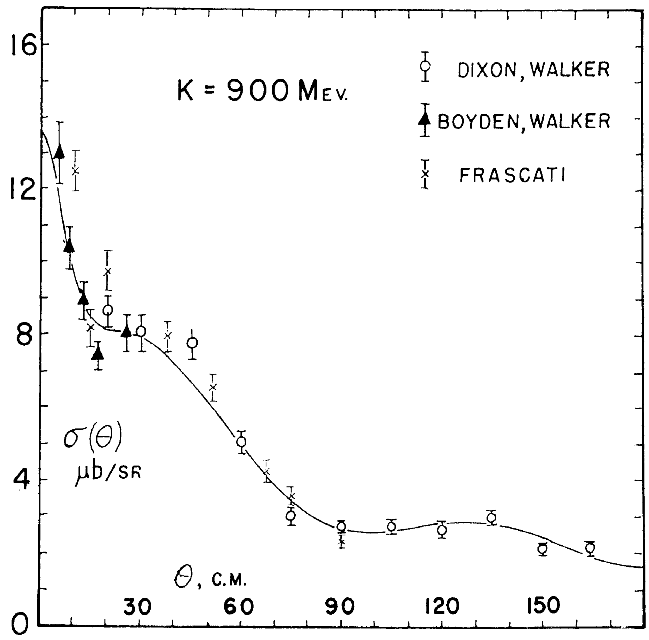

Fig. 3 Angular distribution at 900 MeV. See caption of Fig. 1.

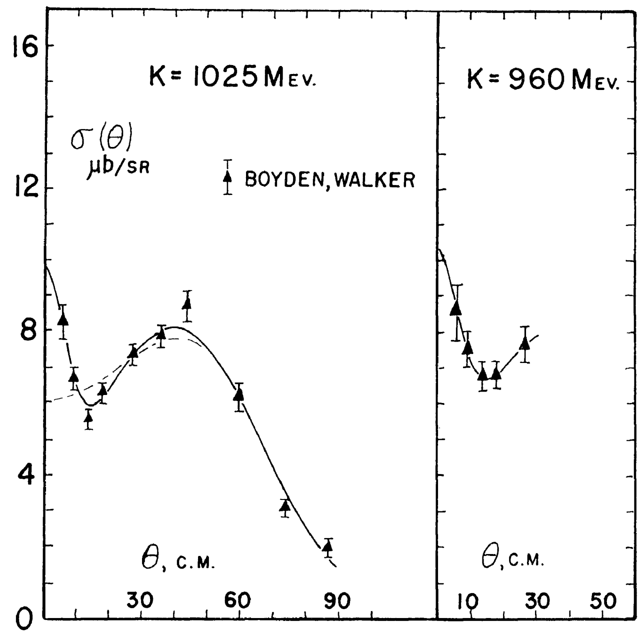

Fig. 4 Angular distributions at 960 and 1025 MeV. See caption of Fig. 1. The dashed curve on the 1025 MeV plot is a fit of $\sigma(\theta)$ alone by a sixth order polynomial in $\cos\theta$, and shows the advantage of the Moravcsik fit.

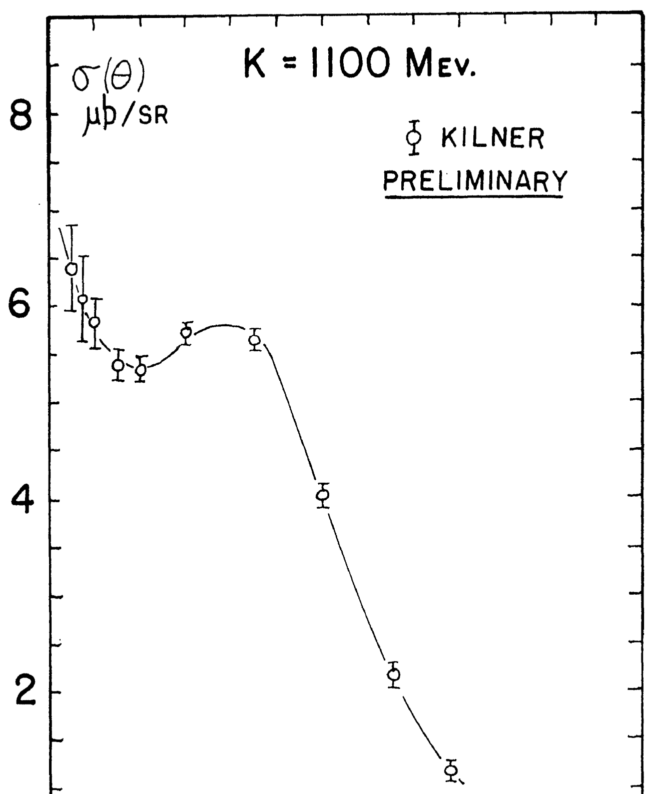

Fig. 5 Angular distribution at 1100 MeV. These are preliminary data of Kilner at Cal. Tech. and the values are not final. The curve is simply drawn through the data points.

meson current, while the remaining terms are the multipole-partial wave decomposition. The (complex) coefficients E_{ij} and M_{ij} refer respectively to absorption of an electric or magnetic multipole of order 2^i, leading to a final state of total angular momentum $J = j/2$. The functions of angle, $f_s(\theta)$, $f_{ij,s}(\theta)$, and $g_{ij,s}(\theta)$ are known, but their explicit forms are not needed for the present discussion. The characteristic angular dependence, $\sin\theta/(1-\beta\cos\theta)$, of the meson current term has been explicitly separated. (β is the pion velocity in the c.m. system, and is 0.97 for $k = 1000$ MeV, for example.) This photoelectric term vanishes at 0° and 180°. Furthermore, at 0° and 180°, only one spin combination contributes, so that the cross section is relatively simple. It is

$$\left.\begin{array}{l}\sigma(0^0)\\ \sigma(180^0)\end{array}\right\} = {}^1/_{8\pi}\left|O \pm E\right|^2$$

where O and E are the following combinations of odd and even parity states:

$$O = \sqrt{2}E_{11} - \sqrt{2}E_{13} + \sqrt{6}M_{23} - \sqrt{6}M_{25} + \sqrt{12}E_{35} + \ldots$$

$$E = \sqrt{2}M_{11} - \sqrt{2}M_{13} + \sqrt{6}E_{23} - \sqrt{6}E_{25} + \sqrt{12}M_{35} + \ldots$$

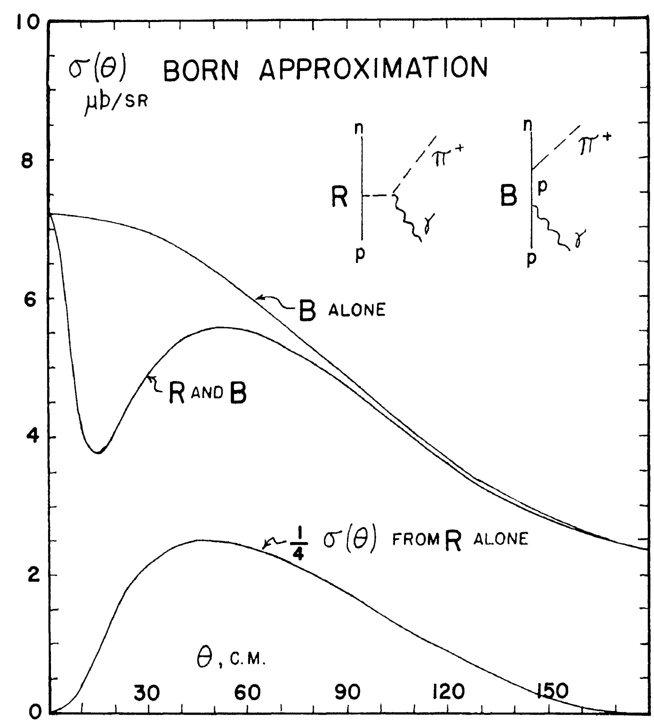

Fig. 6 Angular distribution at 1000 MeV as given by the relativistic Born approximation. Note that the cross section from the photoelectric diagram, R, is quite large and has been divided by 4 in order to plot it conveniently. A " crossed " B diagram does not contribute to π^+ production.

The normalization of the matrix elements, E_{ij} etc., is such that the total cross section resulting from E_{ij} (or M_{ij}) *if* the meson current term were absent ($b=0$) is: $(J+\frac{1}{2})|E_{ij}|^2$, (or $(J+\frac{1}{2})|M_{ij}|^2$).

(a) The photoelectric term

The cross section written above has a second order pole at the non-physical angle where $\cos\theta = 1/\beta$. For this reason, Moravcsik [3] has suggested analysing the experimental data by expanding $(1-\beta\cos\theta)^2\sigma(\theta)$ rather than $\sigma(\theta)$ in a power series in $\cos\theta$. The curves in Figs. 1-4 are such " Moravcsik fits " to the data. χ^2 probabilities for fits with different order polynomials in $\cos\theta$ indicate that at 900 MeV and above a sixth order polynomial gives a satisfactory fit, whereas a fifth order one does not. At lower energies, fifth order polynomials are satisfactory, but do not differ appreciably from the sixth order ones shown in the figures.

Taylor, Moravcsik, and Uretsky [4] have further pointed out that the Moravcsik fit may be used to extrapolate the data to the angle where $\cos\theta = 1/\beta$, and thereby obtain the residue at the pole. This residue is known theoretically in terms of the pion-nucleon coupling constant, so that the extrapolation should yield an experimental value of the coupling constant. Among our data, those at 1025 MeV are the most suitable for carrying out this procedure, since they were all obtained in one experiment and are probably the most self-consistent. The extrapolation is shown in Fig. 7, and yields a value of the coupling constant

$$f^2 = 0.12\pm0.03$$

Because of the large error we have used the pole in a different way, to aid in extrapolating the data to 0°. This was done by including the residue at the pole, calculated from the accepted value of the coupling constant, $f^2 = 0.08\pm0.01$, as one of the points included in the Moravcsik fit. The curves shown in Figs. 1-4 were obtained in this way.

The rapid variations of the cross section with angle in the small angle region arise presumably from the photoelectric term. However, this results from interference effects and not from the photoelectric term alone, as is illustrated by the Born approximation results shown in Fig. 6. For π^+ production, the

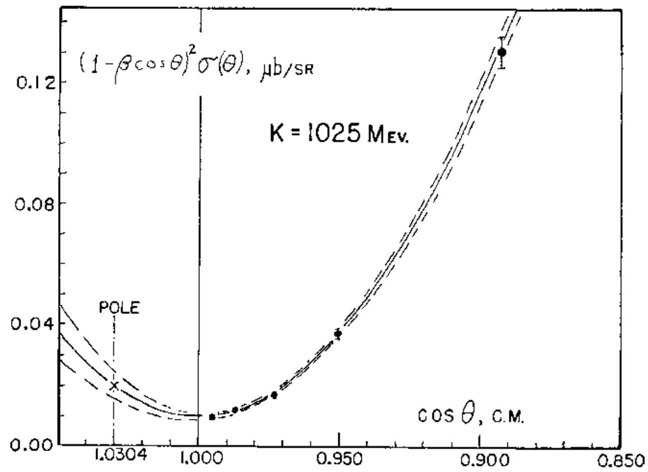

Fig. 7 Extrapolation of $(1-\beta\cos\theta)^2\sigma(\theta)$ to the pole in $\sigma(\theta)$ at the non-physical angle where $\cos\theta = 1/\beta$. This extrapolation shown for the 1025 MeV data leads to a value of $f^2 = 0.12\pm 0.03$ for the pion-nucleon coupling constant. Because of the tremendous range in values of $(1-\beta\cos\theta)^2\sigma(\theta)$, only the data at angles less than 30° are shown in the figure. However, the curve also fits the data at larger angles as shown in Fig. 4.

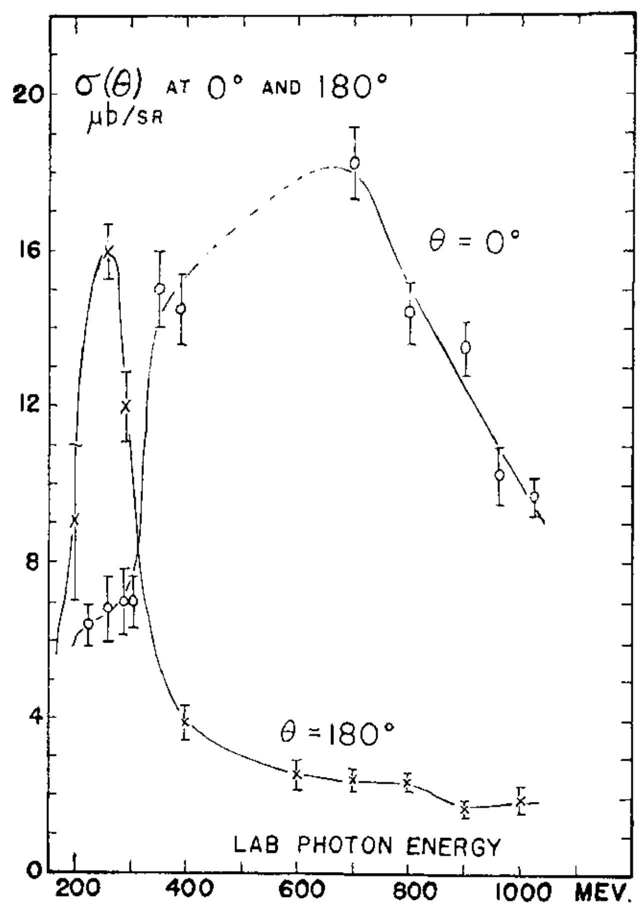

Fig. 8 Cross sections at 0° and 180° as functions of the photon energy, k. Small angle data at lower energies are given in papers by Malmberg and Robinson[5], Uretsky et al [6] and Lazarus et al [7].

Born approximation comes from the two diagrams of Fig. 6, R giving the photoelectric or " retardation " term, and B giving an electric dipole S-wave term, E_{11}, and a smaller magnetic dipole P-wave term, M_{11}. In Fig. 6, it is seen that either term, R or B, alone gives a cross section which varies slowly with angle over the whole region, whereas the two together give a sharp minimum near 14° (for $k = 1000$ MeV), which coincides with the minimum observed at 1025 MeV.

We see that the most striking feature of the small angle data, the steep rise in $\sigma(\theta)$ as θ approaches 0°, is characteristic of the Born approximation. This unfortunately tends to obscure effects which might arise specifically from the higher energy resonances in the pion-nucleon interaction.

(b) The 0° and 180° cross sections

As pointed out above, the cross sections at 0° and 180° have relatively simple expressions in the partial wave analysis, and are not complicated by the photoelectric term. They may thus be especially useful when trying to fit the data by such an analysis. The experimental cross sections at these angles are shown as functions of photon energy in Fig. 8. The interesting feature of the curves is that neither $\sigma(0°)$ nor $\sigma(180°)$ shows a really large change in value as the photon energy, k, passes through the " second resonance " at $k = 750$ MeV. This contrasts with the behaviour near the first resonance at 330 MeV, where both cross sections show a large and rapid change with photon energy.

The behaviour near both resonances may be explained in terms of the expressions given above:

$$\left.\begin{matrix}\sigma(0^0)\\ \sigma(180^0)\end{matrix}\right\} = {}^1/_8\pi \left| O \pm E \right|^2$$

Near 300 MeV, E is mainly the first resonance term, M_{13}, and O is mainly the electric dipole, S-wave term, E_{11}. The behavior of the cross sections at 0° and 180° as the photon energy passes through the resonance is explained by the interference between these two terms in the well known way.

The relatively unspectacular behaviour near the second resonance at $k = 750$ MeV might appear harder to explain. However, it may be understood reasonably well if Peierls' assignment [2)] for this resonance is correct, namely E_{13} (electric dipole, D-wave). Then the resonance term appears in $O = \sqrt{2}E_{11} - -\sqrt{2}E_{13}$ where it is dominated by the larger S-wave term, E_{11}, so that the changes in E_{13} near the resonance produce relatively minor effects in $\sigma(0°)$ and $\sigma(180°)$. This leads to a fairly natural explanation of the behaviour of these cross sections with photon energy, and is one of the arguments in favour of Peierls' assignment for the resonance. It would be more difficult to explain the behaviour of the 0° and 180° cross sections in terms of an even parity resonance.

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