INVERSE PHOTOPRODUCTION REACTION $\pi^- + p \to \gamma + n$ IN FLIGHT

G. Gatti, P. Hillman,* W. C. Middelkoop, T. Yamagata,† and E. Zavattini
CERN, Geneva, Switzerland
(Received May 31, 1961)

The cross section for the photoproduction of pions off free neutrons has in the past been extracted, somewhat precariously, from analysis of photoproduction off deuterium.[1,2] We have now measured the absolute value of the cross section for the process $\pi^- + p \to \gamma + n$, from which the free-neutron photoproduction cross section is immediately calculable using the principle of detailed balance. The experiment was performed at 90° c.m. angle and a pion energy of 72 Mev, which corresponds to a photon c.m. energy of 182 Mev, 53 Mev above threshold. The cross section was measured by detecting the neutrons in a plastic scintillation counter (10 cm thick and 17.6 cm diameter) whose efficiency has been measured.

In order to discriminate against the much more probable charge-exchange reaction $\pi^- + p \to \pi^0 + n$, the energy of the neutrons was measured by time of flight. The time zero was given by the incident pions. In order to reduce this and other backgrounds even further, a coincidence was also required with the γ ray, which was detected in a large lead-glass total absorption Čerenkov counter. All three pulses (incident pion, neutron, and photon) were displayed on a travelling wave oscilloscope and photographed. The film traces were read on IEP, a track-measuring instrument of CERN, after which the CERN Ferranti "Mercury" computer was used to analyze the results and to apply various small corrections. The final time-of-flight spectrum is shown in Fig. 1. The three peaks originate from (1) the photons from neutral pion decay, (2) the neutrons from the inverse photoproduction reaction, and (3) the neutrons from the charge-exchange reaction.

The beam intensity was monitored by an argon-filled ionization chamber[3] calibrated at low intensity against a scintillator telescope. The beam composition was measured by a glycerol Čerenkov counter and found to be $(35.7 \pm 1.0)\%$ pions, $(10.7 \pm 1.0)\%$ muons, and $(53.6 \pm 1.5)\%$ electrons.

The neutron counter efficiency was measured in a separate experiment. The same liquid hydrogen target as used in the main experiment was placed in a beam of neutrons from 190-Mev proton bombardment of a bakelite target inside the cyclotron. The protons knocked out of the hydrogen were detected in a telescope whose energy threshold and channel width had a spatial variation, such that the corresponding scattered neutrons nearly reproduced the spatial and energy distributions of the neutron incident on the neutron counter in the main experiment. The neutron counter was placed in this flux and the fraction of counts in the proton counter which coincided with counts in the neutron counter was measured. In this way the loss of neutrons which were scattered out in the target and target walls in the main experiment was automatically taken into account. The neutron counter efficiency, at a bias equivalent to about 5-Mev recoil protons and for an average neutron

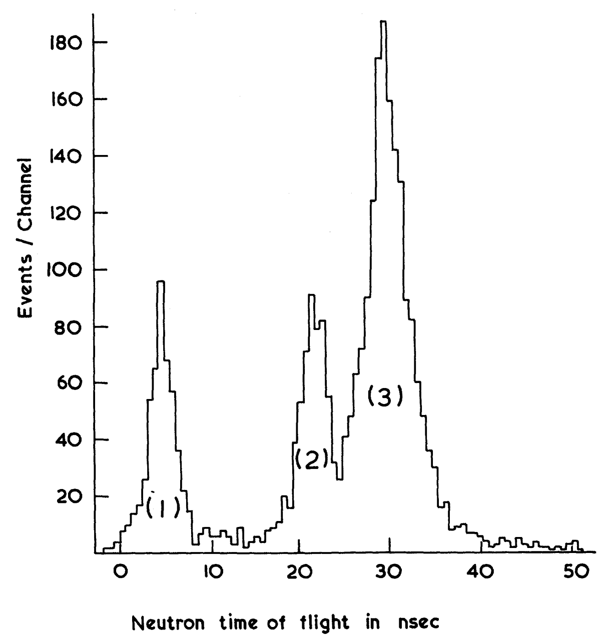

FIG. 1. Neutron time-of-flight spectrum. The peaks are (1) the photons from decay of neutral pions from the charge-exchange reaction, (2) the neutrons from the inverse photoproduction reaction with an average kinetic energy of 26.9 Mev, and (3) the neutrons from the charge-exchange reaction with an average kinetic energy of 13.4 Mev. An average time-of-flight path of 1.45 m was used.

energy of 26.9 Mev, was found to be $(13.6 \pm 0.7)\%$.

The final cross section of 70 ± 7 μb sr^{-1} is based on 505 events (after an empty-target background subtraction of 80 events). This 10% total error is mainly due to a 6% statistical error, a 5% error due to lack of separation between the peaks (2) and (3), an estimated 5% error in the calibration of the neutron counter efficiency, and a 3% error in the measured pion flux. Using the principle of detailed balance, a value of 20.1 ± 2.0 μb sr^{-1} is obtained for a_0^-. This is the 90° differential cross section divided by the statistical factor $W = qq_0(1+k/M)^{-2}$, where q and q_0 are the pion momentum and total energy, k the photon energy (all c.m.), and M the nucleon mass (in units $\mu_\pi = \hbar = c = 1$). Figure 2 shows our result together with those for a_0^+ (the process $\gamma + p \rightarrow \pi^+ + n$), and the values of a_0^- obtained by Adamovich et al.[1] from analysis of the process $\gamma + d \rightarrow \pi^- + p + p$. Also shown are the predictions of dispersion relation theory as given by Chew, Goldberger, Low, and Nambu[4] and as calculated by Hamilton and Woolcock[5] with parameters $f^2 = 0.08$ and $N^{(-)} = 0$. The π^-/π^+ ratio at our photon energy becomes 1.34 ± 0.15, where we used an a_0^+ value of 15.0×10^{-30} cm^2 sr^{-1} as derived from values of Beneventano et al.[6] and Barbaro et al.[7] at nearby energies. This value of π^-/π^+ is in good agreement with the CGLN dispersion theory. However, it is interesting to note that the experimental values of both a_0^- and a_0^+ deviate from the theoretical curves in the same manner around our photon energy. A strong p-wave π-π resonance, which was introduced to explain the nucleon form factors[8,9] and for which an indication was recently found from pion-proton inelastic scattering,[10] is expected to contribute to the photomeson production and to modify the CGLN dispersion relations. Particularly, it has been shown by Ball[11] and by Kawaguchi et al.[12] that the π^-/π^+ ratio at threshold is sensitive to the strength of π-π interaction, but more experiments on a_0^- at lower energies are required to clarify this point.

The guidance and encouragement of Professor G. Bernardini throughout the experiment has been essential to this work. The warm support of Professor P. Preiswerk is acknowledged with gratitude. We thank Dr. Goldschmidt-Clermont who kindly arranged the use of IEP. The help of G. Sicher and B. Smith is gratefully acknowledged as is the competence of the cyclotron, IEP, and hydrogen liquefier staffs.

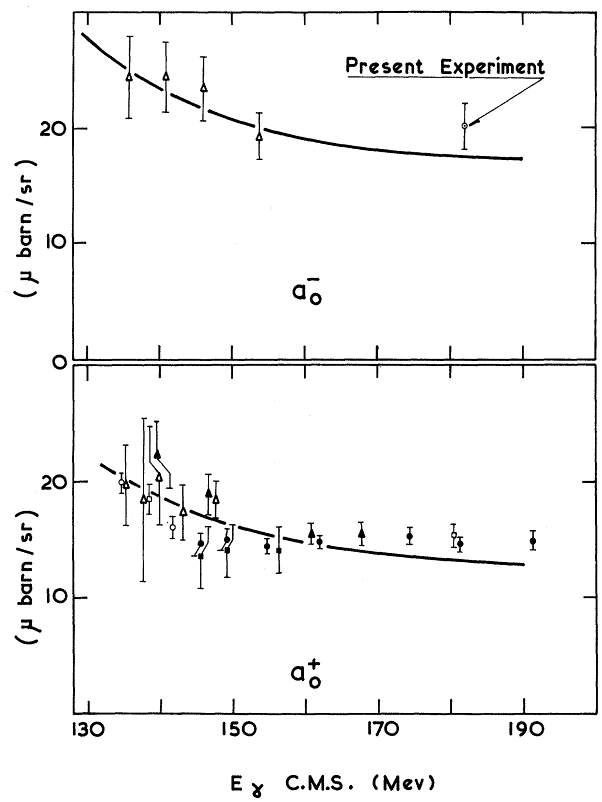

FIG. 2. Values of the π^- and π^+ photoproduction coefficients a_0^- and a_0^+, respectively. ⊙-present experiment; △-Adamovich et al., reference 1; ●-Beneventano et al., reference 6; □-Barbaro et al., reference 7; ▲-J. G. Rutherglen, J. Walker, D. Miller, and G. M. Patterson, Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester (Interscience Publishers, New York, 1960); ○-J. E. Leiss, C. S. Robinson, and S. Penner, Phys. Rev. 98, 201 (1955); and as reported by G. Bernardini, Proceedings of the Ninth Annual Conference on High-Energy Nuclear Physics, Kiev, 1959 (unpublished); ■-G. M. Lewis and R. E. Azuma, Proc. Phys. Soc. (London) 73, 873 (1959). The theoretical curves in both figures are the dispersion relations of Chew et al., reference 4, as calculated by Hamilton and Woolcock, reference 5, with $f^2 = 0.08$ and $N^{(-)} = 0$.

---

*Now at Physics Department, Weizmann Institute, Rehovoth, Israel; Ford Foundation Postdoctoral Fellow.

†Ford Foundation Postdoctoral Fellow.

[1] M. J. Adamovich, E. G. Gorzhevskaya, V. G. Larionova, V. M. Popava, S. P. Kharlamov, and F. R. Yagudina, J. Exptl. Theoret. Phys. (U.S.S.R.) 38, 1078 (1960) [translation: Soviet Phys.—JETP 11, 779 (1960)].

[2]W. P. Swanson, D. C. Gates, T. L. Jenkins, and R. W. Kenney, Phys. Rev. Letters 5, 336, 339 (1960).
[3]D. Harting, J. C. Kluyver, and A. Kusumegi, CERN Report 60-17, 1960 (unpublished). We thank Dr. D. Harting for the use of his ionization chamber.
[4]G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957); referred to as CGLN.
[5]J. Hamilton and W. S. Woolcock, Phys. Rev. 118, 291 (1960).
[6]M. Beneventano, G. Bernardini, D. Carlson-Lee, G. Stoppini, and L. Tau, Nuovo cimento 4, 323 (1956).
[7]A. Barbaro, E. L. Goldwasser, and D. Carlson-Lee, Bull. Am. Phys. Soc. 4, 23 (1959).
[8]R. Hofstader and R. Herman, Phys. Rev. Letters 6, 293 (1961).
[9]W. R. Frazer and J. R. Fulco, Phys. Rev. 117, 1609 (1960).
[10]J. A. Anderson, V. X. Bang, P. G. Burke, D. D. Carmony, and N. Schmitz, Phys. Rev. Letters 6, 365 (1961).
[11]J. S. Ball, Phys. Rev. Letters 5, 73 (1960).
[12]M. Kawaguchi, M. Miyamoto, and Y. Fujii, Nuovo cimento 20, 408 (1961).

COUPLED *S*- AND *P*-WAVE SOLUTIONS FOR PION-PION SCATTERING

B. H. Bransden* and J. W. Moffat†
CERN, Geneva, Switzerland
(Received March 27, 1961)

In a recent paper by Moffat,[1] a set of coupled equations was derived for the inverse partial-wave amplitudes on the basis of the partial-wave analysis of Chew and Mandelstam.[2] We present here the results of a numerical iteration of these equations when coupled S and P waves are treated, and all but two-pion exchange mechanisms are neglected. Up to and including P waves there occur two S-wave subtraction constants, $a_0^I = A_0^I(-\frac{2}{3})$, one P-wave subtraction constant, $a_1^1 = A_1^1(-\frac{2}{3})$, and a constant ξ_1, generated by the P-wave threshold behavior.

By using crossing symmetry, Chew and Mandelstam[2] have deduced that so long as D and higher waves are small the following five conditions hold at $\nu = -\frac{2}{3}$:

$$\tfrac{1}{5}a_0^{\,0} = \tfrac{1}{2}a_0^{\,2} = -\lambda, \tag{1}$$

$$\tfrac{2}{9}a_0^{\,2\prime} = -\tfrac{1}{9}a_0^{\,0\prime} = a_1^{\,1\prime}, \tag{2}$$

$$a_0^{\,0\prime\prime} - \tfrac{5}{2}a_0^{\,2\prime\prime} = 27a_1^{\,1} + 18a_1^{\,1\prime}. \tag{3}$$

All other derivative conditions which may be deduced at the symmetry point depend mainly on the omitted higher partial waves.

The system of equations for the inverse amplitude was programmed for an iterative solution on the CERN mercury computer, supplying λ, the effective pion-pion coupling constant, as a parameter. The constants a_1^1 and ξ_1 are determined by imposing the two crossing-symmetry conditions (2). The solutions, as functions of the single parameter λ, are used to determine the quantities entering (3). The extent to which the condition (3) is satisfied is a test of the consistency of the theory, and, as we shall see, this does not impose any limitations on the values of λ employed. If the solutions are to be consistent with the Mandelstam representation, no complex poles may occur in $A_l(\nu)$. It has been verified that no such poles occur for the solutions presented in this Letter.

Seven or eight interation cycles were found to be sufficient to determine the inverse amplitudes to better than 1%, when starting from given values of ξ_1 and a_1^1. By varying ξ_1 and a_1^1 in a systematic manner until Eqs. (2) were satisfied to 1-2%, these constants and the calculated phase shifts for a given λ were found to be of the same order of accuracy. In a preliminary calculation[3] the conditions (2) were only satisfied to 15%, but this accuracy has been found to be insufficient to obtain a quantitatively correct set of phase shifts.

The numerical calculations have shown clearly that the range of λ is limited. For each negative λ (corresponding to attractive S-wave forces) with $|\lambda| \leq 0.5$, a single positive value of ξ_1 can be found so that conditions (2) are satisfied. These solutions are characterized by a very small P-wave phase shift and correspond to those computed by Chew, Mandelstam, and Noyes.[4] However, these solutions with positive ξ_1 completely fail to satisfy condition (3) and do not, therefore, represent cases of physical interest. For negative values of λ, other solutions are found having a negative value of ξ_1. For values of $|\lambda| \geq 0.45$ a bound state in the $I=0$ state occurs ($\cot\delta_0^{\,0}$ becomes negative near zero energy), but