Elastic Photoproduction of π^0 Mesons from Deuterium*

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(Received September 27, 1955)

The differential cross section for the reaction $\gamma+d\rightarrow\pi^0+d$ has been measured for a broad spread (35 Mev) of γ-ray energies centered at about 280 Mev. The values as measured for three angles of the π^0 meson in the laboratory system are as follows:

$\theta(\pi^0)$	$d\sigma/d\Omega$ (μb/sterad)
58°	9.0±2.4
80°	4.7±1.2
105°	2.8±0.8

In addition to the above uncertainties based on counting statistics, there is an absolute uncertainty of about 20% because of uncertainties in detection efficiency and bremsstrahlung spectrum. The results are in good agreement with similar, earlier measurements at Cornell University and with the theory of Chappelear.

INTRODUCTION

THE photoproduction of π^0 mesons by the reaction

$$\gamma+d\rightarrow\pi^0+d,$$

where the deuteron recoils intact, is known as the "elastic" process, as opposed to the alternative "inelastic" reaction

$$\gamma+d\rightarrow\pi^0+p+n.$$

The theory of the elastic process has been investigated by Francis and others[1] and more recently by Chappelear.[2] Since the deuteron remains intact, the elastic π^0 production is a coherent superposition of the production from the proton and the neutron. The nature of the interference, whether it is constructive or destructive, and its magnitude depend on the relative phase and magnitudes of the coupling of the meson to the proton and to the neutron. These coupling parameters are of basic interest in meson theory.

Recently, two groups of workers[3] at Cornell University have measured the differential cross section averaged over a rather wide spread in incident γ-ray energies and for a limited range of π^0 angles. Their results, when compared with theory, are convincing evidence that the interference is constructive. Their data also support the more refined calculations of Chappelear where the impulse approximation calculation is corrected for the effect of the final-state interaction of the meson and the deuteron. (This so-called "multiple scattering" effect reduces the earlier calculated cross section by about 40% at all angles.)

This is a report of work carried out at the Massachusetts Institute of Technology 350-Mev synchrotron similar to one of the two experiments at Cornell.

EXPERIMENTAL PROCEDURE

The experiment was carried out using 330-Mev bremsstrahlung from the M.I.T. synchrotron. A CD_2 (deuterated paraffin) target 85 mg/cm² thick was employed with CH_2 subtraction. The experimental arrangement is shown in Fig. 1. The deuteron recoil was detected with a counter telescope in coincidence with the detection of one of the γ's from the decay of the π^0. While the measurement of the angle and energy of the deuteron alone would have completely determined the kinematics of the reaction, the coincidence was required to reduce the background contribution of deuterons from carbon, which strongly affected the subtraction statistics.

Even if only the deuteron were detected, the only reaction that could be confused with the elastic photomeson reaction is the process of Compton scattering $\gamma+d\rightarrow\gamma+d$. Demanding the γ coincidence does not prevent the Compton process from contributing, but the cross section for the process is believed small compared to that for the elastic photomeson reaction.

The deuteron telescope consisted of a thin (0.020-in.) 1-in. diameter, NaI(Tl) scintillator backed by a thick ($\frac{1}{2}$-in.) $2\frac{3}{4}$-in. diameter NaI(Tl) crystal. The first crystal was viewed by a DuMont 6292 photomultiplier tube, the second by a DuMont 6363. The deuterons were distinguished from the protons by the well-known method using dE/dx and energy. The deuterons of interest stopped in the second crystal giving a scintillation pulse proportional to the incident energy. The associated pulse in the thin first crystal was roughly proportional to dE/dx at that energy. The heights of pulses from the two counters were analyzed by means of an oscilloscope. Simultaneously, one pulse was presented on the X-plates, the other pulse on the Y-plates. The resulting traces were photographed by a camera

* This work was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission. Reproduction of this article in whole or in part is permitted for any purpose of the United States Government.
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‡ Now at Westinghouse Corporation, Pittsburgh, Pennsylvania.
[1] N. C. Francis and R. F. Marshak, Phys. Rev. 85, 496 (1952); Heckrotte, Henrick, and Lepore, Phys. Rev. 85, 490 (1952); N. C. Francis, Phys. Rev. 89, 766 (1953).
[2] John Chappelear, Phys. Rev. 99, 254 (1955).
[3] Wolfe, Silverman, and DeWire, Phys. Rev. 99, 268 (1955); H. L. Davis and D. R. Corson, Phys. Rev. 99, 273 (1955).

with continuously moving film. When the film was analyzed, the end points of the traces gave the values of both dE/dx and energy. For particles of the same charge and the same energy, the dE/dx depends on the particles' mass M, being proportional to $M^{0.8}$ in the energy range of interest here. This allowed a reasonable separation of deuterons from protons, as shown in Fig. 2. The energy scale on the oscilloscope was calibrated by placing the deuteron telescope in the 90-Mev external proton beam of the Harvard cyclotron and varying the beam energy by means of absorbers.

The γ counter consisted of a plastic scintillator (5 in. in diameter, $\frac{1}{2}$ in. thick) preceded by a $\frac{3}{8}$-in. thick lead plate to convert γ's to electron-positron pairs. In front of the lead converter were two inches of graphite to reduce the incident charged particle flux reaching the scintillator. The scintillator was viewed by a RCA 6199 photomultiplier tube.

While the use of γ coincidences reduces background subtraction, it leads to difficulties in estimating the efficiency with which the reaction is detected. The counter efficiency can be divided into two parts, geometric and intrinsic. The geometric efficiency is a measure of the probability that the counter intercepts one of the two π^0-decay gammas. This efficiency is at maximum when the counter is placed along the direction of the π^0 recoil, and its value as a function of angle and energy can be calculated in a straightforward manner.[4] The intrinsic efficiency is a measure of the probability that the intercepted γ leads to one or more electrons reaching the scintillator and that the electronic bias be such that an electron is detected.

To measure this intrinsic efficiency, the entire γ counter was placed in monochromatic electron beam made available to us by G. Pugh. This electron beam of known energy was produced by using the Massachusetts Institute of Technology synchrotron x-ray beam, a converter, and an analyzing magnet. The collimated electron beam passed through two monitoring scintillation counters before entering the γ counter, complete with lead and graphite. The γ-counter bias was set to detect particles giving a pulse more than one-half the size of that given by minimum ionizing particles passing completely through the scintillator. The efficiency for detecting electrons was measured for a series of electron energies. The efficiency for detection of gammas was then estimated by using the measured electron detection efficiency and the statistics of the shower production process for γ's and electrons as given by Wilson's Monte Carlo calculations.[5]

The product of detection efficiency and effective incident bremsstrahlung flux contributing to the photomeson reaction was a fairly rapidly varying function

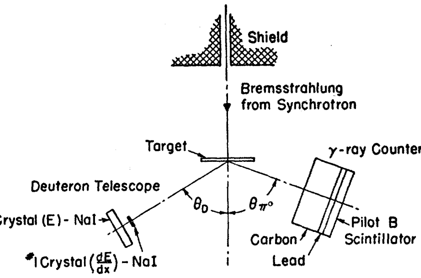

FIG. 1. Experimental arrangement for detection of recoil deuterons in coincidence with π^0-decay gamma rays.

of the position of reaction in the CD_2 target and the angle of deuteron recoil. A numerical integration was made of this efficiency-spectrum product over the area and thickness of the target, the area of the deuteron detector and the deuteron energy interval analyzed with the deuteron telescope. The average π^0 differential cross section is then given by

$$(d\sigma/d\Omega)_{\pi^0\,\mathrm{lab}}=\mathrm{yield}/nI,$$

where n = number of deuterium atoms per cm^2 and

$$I=\frac{1}{V}\int\int\int(d\Omega_{\pi^0\,\mathrm{lab}}/d\Omega_{d\,\mathrm{lab}})dE_\gamma/dE_d \times(dN_\gamma/dE_\gamma)\xi dVdE_d d\Omega_d;$$

E_γ and E_d are the energies of the incident γ and the recoil deuteron, V is the volume of the target, N_γ is the number of gammas in the bremsstrahlung spectrum, and ξ is the efficiency for detecting the π^0 by means of one of its decay γ rays.

The results of the cross-section measurements are given in Table I and the values for x-ray energies centered about 280 Mev are plotted in Fig. 3. The spread in x-ray energies over which the cross sections are averaged is large, the distributions being about 35 Mev wide at half-maximum.

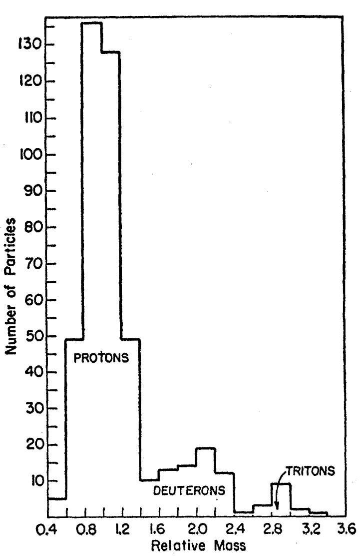

FIG. 2. Resolution of particles of different mass as produced in a Pb target. (Relative mass scale calculated from range-energy relationships.)

[4] These and our other kinematic calculations were based on *Tables of Nuclear Reaction Kinematics at Relativistic Energies*, by J. H. Malmberg and L. J. Koester (Physics Department, University of Illinois, Urbana, Illinois).

[5] R. R. Wilson, Phys. Rev. **86**, 261 (1952).

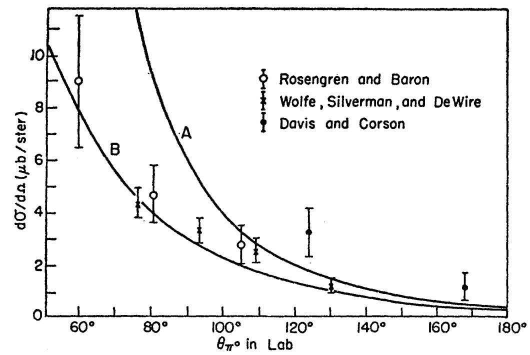

FIG. 3. Comparison of experimental results with theory. Theoretical curves, by Chappelear,[2] are for the case of constructive interference: *A*—impulse approximation; *B*—impulse approximation with correction for "multiple scattering."

The uncertainties indicated in Fig. 3 are standard deviations based on counting statistics. There is an additional absolute uncertainty of about twenty percent because of uncertainties in detection efficiency and bremsstrahlung spectrum. Silverman *et al.* quote a similar absolute uncertainty of 25%.

The theoretical curves shown in Fig. 3 are based on a $2+3\sin^2\theta$ center-of-mass angular distribution of π^0 mesons from free protons and constructive interference between the production from the proton and the neutron.

The agreement of our results with the Cornell experimental data is seen to be good.

TABLE I. Differential cross section for elastic photoproduction of π^0 mesons from deuterium.

$\theta_{\pi^0\text{ lab}}$ (degrees)	E_γ at center of spread (Mev)	$(d\sigma/d\Omega)_{\pi^0\text{ lab}}$ (μb/sterad)
58	280	9.0±2.4
76	246	2.8±1.0
80	279	4.7±1.2
102	229	2.4±0.9
104	253	2.7±1.0
105	280	2.8±0.8

ACKNOWLEDGMENTS

We are pleased to acknowledge the assistance of Charles Drane and Robert Wertheim in the construction and operation of the detection apparatus, and that of Michael Nauenberg in the calculation of the π^0-detection efficiency. We are indebted to the Harvard Cyclotron Group for the use of their machine in calibrating our apparatus.

PHYSICAL REVIEW VOLUME 101, NUMBER 1 JANUARY 1, 1956

78-Mev $\pi^\pm$ Meson Scattering from Lithium*†

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The angular distributions of 78-Mev $\pi^\pm$ mesons scattered elastically from lithium have been measured. The distributions have been analyzed by combining coherently the scattering amplitudes for the individual pion-nucleon interactions, and weighting each amplitude by a form factor determining the ability of the struck nucleon to absorb the momentum recoil and remain in its same state in a nuclear harmonic oscillator well. Corrections are applied for solid angle transformations between the pion-nucleus and pion-nucleon center-of-mass systems, the effect of the required nuclear elastic scattering upon the available phase space in the pion-nucleon system, and an initial momentum distribution for the nucleons. The simple Born approximation treatment provides agreement with the pronounced dip at 75° and the backward rise of the experimental curves.

A. INTRODUCTION

AN examination of the "elastic"[1] scattering of (78±4.7)-Mev positive and negative pions from lithium has been made. This represents an extension of previous measurements of the scattering on aluminum as part of our program of investigating the behavior of the angular distribution of the elastic scattering of pions on complex nuclei. The variable parameters, in addition to the angle, are the pion charge and energy, and the atomic number of the target nucleus.

The familiar optical model method,[2] generalized here to treat the scattering from a nucleus as a solution to a Schrödinger equation involving a central potential, has been applied to the scattering of fast nucleons by

* This research was supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Submitted in partial fulfillment by R. W. of the requirements for the degree of Doctor of Philosophy in the Faculty of Pure Science, Columbia University.

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[1] The sum of true elastic plus nearly elastic scattering is actually measured. The term "elastic" for the experimental results will usually imply this sum.

[2] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949); K. M. Watson, Phys. Rev. **89**, 575 (1953).