$\pi^{\pm}$ and π^0 Production by Polarized Photons in the Resonance Region*†

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(Received 13 March 1972)

We have measured the cross sections at 90° c.m. for $\pi^{\pm}$ and π^0 photoproduction with polarized photons. The photon energies ranged from 0.8 to 2.2 GeV. We compare the resonant "bumps" in the cross section with theoretical models. The measured asymmetry agrees with a quark-model calculation though the predicted cross sections are low.

The quark model has enjoyed sufficient success as to be almost believable.[1] Few experiments, however, test the spatial distribution of these elusive particles in their nuclear "atom." Photoexcitation of the baryon resonances does this since the transitions combine electric and magnetic spin-flip amplitudes of differing Δl. The amplitude relates the quark magnetic moment to the radial size of the quark atom. This experiment studies baryonic excitation through single meson photoproduction at 90° in the center-of-mass system with plane-polarized photons where there is a large correlation between the plane of production and electric or magnetic multipolarity.[2]

We have measured three reactions:

$$\gamma + p \to \pi^0 + p, \quad (1)$$

$$\gamma + p \to \pi^+ + n, \quad (2)$$

$$\gamma + d \to \pi^- + p + p_{\text{spectator}}. \quad (3)$$

The photon energy ranged from 0.8 to 2.2 GeV. Polarized photons were produced by bombarding an aligned diamond crystal with 5.5-GeV electrons from the Cambridge Electron Accelerator.[3,4] A typical photon spectrum measured with a pair spectrometer[5] is shown in Fig. 1 with a calculated best fit to the curve smeared by beam spread and crystal imperfection; we then computed the polarization given our fitting parameters. In all the measured reactions two product particles were detected in coincidence. The momentum vector and time of flight of the p, π^+, and π^- in Reactions (1) to (3), respectively, were measured with the Moby Dick spectrometer.[6] A second particle detector[7] was used to identify the π^0, n, and p, respectively, and to restrict our measurement to the two-body reaction. We measured backgrounds by setting this second detector at two off angles on either side of its kinematically

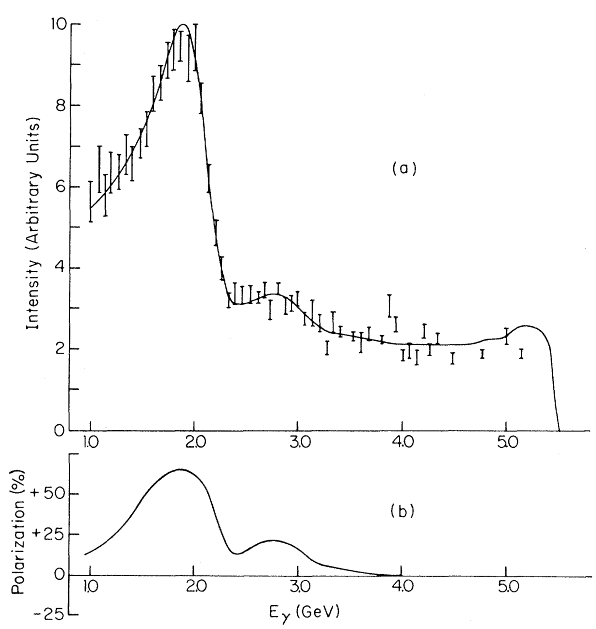

FIG. 1. (a) A typical measured photon spectrum produced by the electron beam impinging on the diamond target. The solid line represents a best fit varying the unknown beam dispersion and diamond orientation as parameters. (b) The calculated photon polarization using these parameters. Our runs utilized the photons in the region of maximum polarization.

correct setting. The resulting correction varied from negligible to 10% going from lowest- to highest-energy runs.

Our instrumental acceptances were determined by a Monte Carlo program. The neutron counter for Reaction (2) had been previously calibrated.[7] Our π^+ and π^- cross-section data are in agreement with previously published cross-section measurements with unpolarized photons.[2] In Reaction (1) the counters used to detect π^0's through their decay γ rays were inappropriate for absolute cross-section measurements. Thus our cross sections for this reaction were obtained by combining yield ratios for parallel and perpendicular photon polarizations with previously published cross sections.[8]

Our results are quoted as two cross sections, $d\sigma_\perp$ and $d\sigma_\parallel$, which correspond to those obtained for a photon beam perfectly polarized in a plane perpendicular or parallel to the meson production plane. These results are shown in Fig. 2. The errors shown are due to counting statistics alone; additional systematic errors are quoted in the captions. In addition, a sample of the asymmetries is given in Table I.[9]

These results fall in the region dominated by the $F_{15}(1688)$, the $D_{15}(1670)$, and the $F_{37}(1950)$ resonances. At 90° in the center-of-mass system these resonance amplitudes tend to be enhanced with respect to the t- and u-channel exchange amplitudes.

The F_{15} (or D_{15}) bump is clearly evident in both π^0 and π^+ photoproduction. It is absent in π^- photoproduction as has been noted before[2,10] and this is in agreement with quark models[10] which predict that the neutron cannot be photoexcited into the F_{15} resonance. The quark models predict an asymmetry A,

$$A = (d\sigma_\perp - d\sigma_\parallel)/(d\sigma_\perp + d\sigma_\parallel),$$

equal to zero for the F_{15}; this is equivalent to the statement that the helicity $-\frac{1}{2}$ amplitude vanishes, which is, in turn, equivalent to an apparently fortuitous cancelation between electric and magnetic multipoles.[11] The π^+ data are compatible with this prediction. The π^0 data show structure that would require strong interference phenomena to be compatible with the prediction. In absolute value the bumps are larger than the prediction[10]

$$d\sigma_\perp(\pi^0) = d\sigma_\parallel(\pi^0) = 0.1 \pm 0.03\ \mu\text{b/sr}$$

for the F_{15} whereas our bump in $d\sigma_\parallel$ is greater than 1.0 μb/sr.

Near $E_\gamma = 1.5$ GeV we expect the F_{37} to show in the cross section. Nonrelativistic quark models[10] predict $A = 0.88$ for the F_{37} and hence the resonance should be seen mainly in $\sigma_\perp$. This comes about since the Δ resonances are excited by pure quark spin-flip. In addition, isotopic spin and

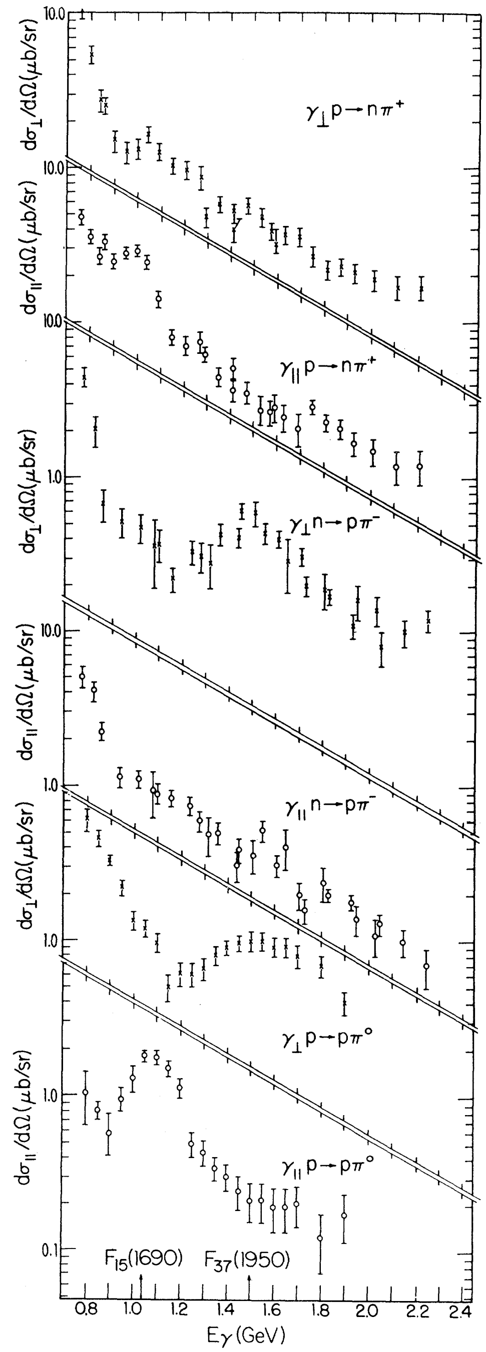

FIG. 2. $d\sigma_\perp$ and $d\sigma_\parallel$ for π^+, π^-, and π^0 photoproduction are shown as a function of photon bombarding energy. Errors shown are statistical only. We estimate an additional systematic error of 15%.

TABLE I. A sample (Ref. 9) of the measured asymmetries $A=(d\sigma_{\perp}-d\sigma_{\parallel})/(d\sigma_{\perp}+d\sigma_{\parallel})$ for π^+, π^-, and π^0 photoproduction as a function of photon energy. Errors shown are statistical only. We estimate an additional systematic error of $\Delta A=\pm 0.10$.

E_γ (GeV)	π^+	π^0	π^-
0.7	0.49 ± 0.06	···	−0.14 ± 0.10
0.8	0.31 ± 0.08	0.73 ± 0.10	−0.41 ± 0.09
0.9	−0.10 ± 0.05	0.71 ± 0.09	−0.40 ± 0.08
1.0	−0.24 ± 0.06	−0.10 ± 0.12	−0.52 ± 0.08
1.1	−0.10 ± 0.06	−0.42 ± 0.14	−0.50 ± 0.06
1.2	−0.10 ± 0.06	−0.09 ± 0.09	−0.31 ± 0.11
1.3	+0.05 ± 0.05	0.20 ± 0.10	−0.26 ± 0.09
1.4	0.0 ± 0.05	0.55 ± 0.08	0.11 ± 0.12
1.5	0.20 ± 0.10	0.61 ± 0.11	0.33 ± 0.09
1.6	0.22 ± 0.09	0.67 ± 0.07	0.18 ± 0.09
1.7	0.10 ± 0.10	0.61 ± 0.07	0.03 ± 0.09
1.8	0.08 ± 0.08	0.73 ± 0.10	−0.03 ± 0.09
1.9	0.06 ± 0.11	···	···
2.0	0.14 ± 0.14	···	−0.15 ± 0.12

the above quark models predict for the F_{37} alone and either polarization that

$$d\sigma(\pi^-)=d\sigma(\pi^+)=\tfrac{1}{2}d\sigma(\pi^0).$$

Our results seem to be compatible with this prediction for the π^- and π^0. In the case of the π^+ there is no obvious bump; however, the tail of the F_{15} resonance and poor statistics may partially account for this. Again, the cross section we measure is high. Reference 10 predicts $d\sigma_{\perp}(\pi^0)=0.26\pm0.06$ μb/sr at the $F_{37}(1950)$ peak; we get $d\sigma_{\perp}(\pi^0)\simeq 0.9$ μb/sr, taking into account an estimated background contribution to the measured cross section.

It should be remembered that a model such as Ref. 10, whose parameters are fixed by the static magnetic moment of the proton, already underestimates the better understood photoexcitation of the $\Delta(1236)$.[2] Other sufficiently large amplitudes resonating near $\sqrt{s}=1688$ and 1950 MeV would increase the measured cross section and tend to explain the quantitative disagreement. However, such amplitudes as are known[12] are highly inelastic and therefore small except for the $D_{15}(1670)$. The latter, nonetheless, would give a bump in the π^- cross section.

In summary, our measured polarization asymmetries for the F_{15} and F_{37} resonances are compatible with quark-model predictions. The measured cross sections, on the other hand, confirm a disagreement with these models for the F_{15} and appear to extend the disagreement to the F_{37}. However, it is obvious that many more data will be needed to disentangle the resonant effects in this region.

*Work supported in part by the U. S. Atomic Energy Commission under Contracts No. AT(11-1)-3063, No. AT(11-1)-3069, and No. AT(11-1)-3525.

†The experiments summarized here are described in greater detail in the following references: J. Alspector, Ph.D. thesis, Massachusetts Institute of Technology, 1971 (unpublished); D. Fox, Ph.D. thesis, Massachusetts Institute of Technology, 1971 (unpublished); C. Nelson, Ph.D. thesis, Massachusetts Institute of Technology, 1971 (unpublished).

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[8]R. Alvarez, Z. Bar-Yam, W. Kern, D. Luckey, L. S. Osborne, S. Tazzari, and R. Fessel, Phys. Rev. Lett. 12, 707 (1964).

[9]Our complete results in tabular form and results for A with smaller errors are available by writing to D. Luckey, Rm 24-036, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

[10]We compare chiefly with L. A. Copley, G. Karl, and E. Obryk, Nucl. Phys. B13, 303 (1969). See also a relativistic model by R. P. Feynman, M. Kislinger, and F. Ravndal, Phys. Rev. D 3, 2706 (1971), and an

intercomparison of photoproduction amplitudes using various assumptions about quarks by L. S. Kisslinger and H. Feshbach, Ann. Phys. (New York) 66, 651 (1971).

[11]This cancelation is demonstrated experimentally by the lack of bumps in the 0° and 180° differential cross sections. This becomes an input to the quark models and is used to evaluate the radial-wave-function parametrization with respect to the quark magnetic moments. However, some recent data by T. Fujii, H. Okuno, S. Orito, H. Sasaki, T. Nozaki, F. Takasaki, T. Takikawa, K. Amako, I. Endo, K. Yoshida, M. Higuchi, M. Sato, and Y. Sumi, Phys. Rev. Lett. 26, 1672 (1971), shows a small "bump" in π^+ photoproduction at 180°.

[12]See the Argand diagrams in A. Rittenberg *et al.* (Particle Data Group) Rev. Mod. Phys. 43, S1 (1971).

Search for $\bar{\nu}_e + e^-$ Scattering*

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(Received 23 March 1972)

An improved cross-section upper limit of 1.9 times that of $V-A$ theory is determined for the reaction $\bar{\nu}_e+e^-\rightarrow\bar{\nu}_e+e^-$. The target, a 7.84-kg plastic scintillator, was enclosed by a composite 330-kg NaI and 2200-liter liquid anticoincidence detector, and was operated in a fission $\bar{\nu}_e$ flux of 2.2×10^{13} cm^{-2} sec^{-1}. We note some constraints which this limit imposes on theoretical conjectures.

In this Letter we present the current status of our continuing search for the elastic scattering of electron antineutrinos $\bar{\nu}_e$ by electrons using a fission reactor as a $\bar{\nu}_e$ source.[1] As will be seen, we have substantially improved the previous elastic scattering cross-section upper limit (< 4 times that of $V-A$ theory), enabling us to place more restrictions on the interactions which are permitted. The equipment is much the same as that reported earlier except for some additions designed to reduce backgrounds. The results also reflect an increase in total run time from the 15 days on which the first report was based, to 147 days, live time. In brief, the detector consisted of a 7.84-kg segmented plastic scintillator target block entirely surrounded by a 330-kg NaI anticoincidence detector[1] which was in turn enclosed by a 2200-liter liquid anticoincidence detector. The elastic scattering mode accepted only events occurring in the plastic, in anticoincidence with these outer detectors. The system was operated concurrently in the mode designed to detect inverse β decay, $\bar{\nu}_e+p\rightarrow n+e^+$, in the plastic target, so as to study the background from this reaction as well as to determine the fission $\bar{\nu}_e$ spectrum. Changes made in the detector included the addition of 2.5 cm of Pb around the NaI scintillator (for a total of 6.3 cm) to provide further shielding against reactor γ rays. A cadmium sheet immediately external to the Pb reduced the γ background arising from neutron capture. Further shielding against reactor neutrons and γ's was provided by the addition of water tanks where practicable. The result of these measures was to reduce the reactor-associated rate as measured by the NaI detector from $R=1.3\pm0.4$ counts/min in the 4.1–10.3-MeV region to levels consistent with statistical fluctuation in the rate of radioactivity, i.e., $R\leq0.15$ counts/min. Cosmic-ray-associated backgrounds were reduced by the addition of a large rectangular liquid anticoincidence detector (2.59 m × 1.43 m × 0.28 m) above the cylindrical liquid anticoincidence detector. Measurements of events associated with muons, such as those due to neutrons and those produced by muon capture which lead in turn to decays of B^{12} (end point, 13.4 MeV), suggested the incorporation of electronic vetoes which were effective in a large fraction of these cases.

The rapidly falling spectrum characteristic of the background makes it essential to maintain a continuous check of the system gain. Such a check is provided by the β decay (3.2-MeV end point) of Bi^{214} contaminant. The procedure used was to measure the rate of Bi^{214} decay as identified by a delayed daughter α particle (7.7 MeV), $\tau_{1/2}=164$ μsec. The energy associated with a preselected Bi^{214} rate was taken as the reference value and all runs were normalized to it. The absolute energy scale was set to within ± 2% by means of a Tl^{206} γ source (2.62 MeV). Both sources were viewed by the entire plastic in anticoincidence with the surrounding NaI. The mean correction to the overall gain of the system as measured by the B^{214} was within ± 2%. Figure 1 shows these calibration spectra.