tive positions of the laser modes and the atomic resonance, γ_a and γ_b are the decay constants for the $3s_2$ and $2p_4$ states respectively, and $\gamma_{ab} = \frac{1}{2}(\gamma_a + \gamma_b)$. The rates of excitation to the $3s_2$ and $2p_4$ states per unit volume per unit time are denoted by Λ_a and Λ_b respectively. The symbol $\Delta = 2g\mu_B H/h$, where g, μ_B and h are the g factor, Bohr magneton, and Planck's constant in that order. The symbol f represents the fundamental beat frequency of the laser. For many-mode operation, terms appear showing resonances at $\Delta \pm 2f = 0$, $\Delta \pm 3f = 0$, etc. The correspondence of these calculated terms with the dips in trace z and even trace x of Fig. 2(c) is apparent. Oscillating terms (not shown) at f, $2f$, etc., also occur. An incidental point of interest is that the width of the fourth-order Lorentzian resonance is given by γ_a permitting, for resolved fourth-order peaks, a measure of the upper state lifetime.[13]

We feel that one of the most striking features of this experiment is the contribution to the time-independent scattering produced by amplitude-modulating the saturating field. Our two-mode calculation shows that the terms giving that contribution arise from the interaction of the same atom with both laser modes, the atom interacting with each mode twice. We suggest that an appropriate way of viewing such a process is to regard it as an interference of two time-dependent second-order processes which produces a time-independent contribution to the saturated susceptibility.

The authors wish to acknowledge the interest of J. P. Gordon in this work and the assistance of L. J. Heilos and W. R. Wolff in the construction of apparatus.

---

[1]See for example, P. A. Franken, Phys. Rev. 121, 508 (1960).

[2]A. Javan, Bull. Am. Phys. Soc. 9, 489 (1964).

[3]R. H. Cordover, A. Szöke, and A. Javan, Bull. Am. Phys. Soc. 9, 490 (1964).

[4]L. E. Hargrove, R. L. Fork, and M. A. Pollack, to be published.

[5]A. G. Fox and T. Li, Bell System Tech. J. 40, 453 (1961).

[6]It should be noted that this condition is not typical of laser action, but is forced by the intracavity modulator.

[7]This estimate of the mode phase relations was made on the basis of the known optical spectrum and the output pulse shape (half-width $\sim 2.5 \times 10^{-9}$ sec) as observed on a sampling oscilloscope.

[8]This calculation used a value for the $2p_4$ state lifetime of 0.67×10^{-8} sec obtained by an independent measurement made at the same operating pressure (0.1 Torr ^{20}Ne and 0.7 Torr He) as the present experiment.

[9]A. Corney and G. W. Series, Proc. Phys. Soc. (London) 83, 207 (1964).

[10]The second-order peak [Fig. 2(c)] provides a measure of the lower state lifetime; however, fourth-order processes also contribute to the peak half-width, the angular dependence of the ratio of second- and fourth-order contributions causing significant (e.g., 8 %) variations in the apparent half-width as a function of observation angle. Valid lower state lifetime measurements thus require operation at low saturation levels or the addition of appropriate higher order corrections.

[11]A contribution to the magnetic field-dependent scattering from the process $\langle m = \pm 1| \rightarrow \langle m = 0| \rightarrow \langle m = \pm 1|$ is unique to a fourth-order induced event, and can be thought of as arising from the precession of the depletion-induced polarization of the upper ($3s_2$) state.

[12]W. Lamb, Phys. Rev. 134, A1429 (1964). The authors are indebted to Professor Lamb for access to his manuscript prior to publication and for clarification of certain portions of that manuscript.

[13]We also note that deviations of theory and experiment remaining after accounting for higher order effects, particularly polarization discrepancies, should provide a measure of disorienting collision cross sections.

PHOTOPRODUCTION OF π MESONS BETWEEN 0.9 AND 4.0 BeV*†

R. Alvarez, Z. Bar-Yam, W. Kern, D. Luckey, L. S. Osborne, and S. Tazzari‡
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

and

R. Fessel
Cambridge Electron Accelerator, Cambridge, Massachusetts
(Received 2 April 1964)

We have measured protons and gamma rays in time coincidence using the apparatus shown schematically in Fig. 1. It consists of two rotating platforms copivoted about a liquid hydrogen target through which passes a photon bremstrahlung beam from an internal target in the Cambridge Electron Accelerator. The larger platform carries, in order, two quadrupoles ($Q1$ and $Q2$)

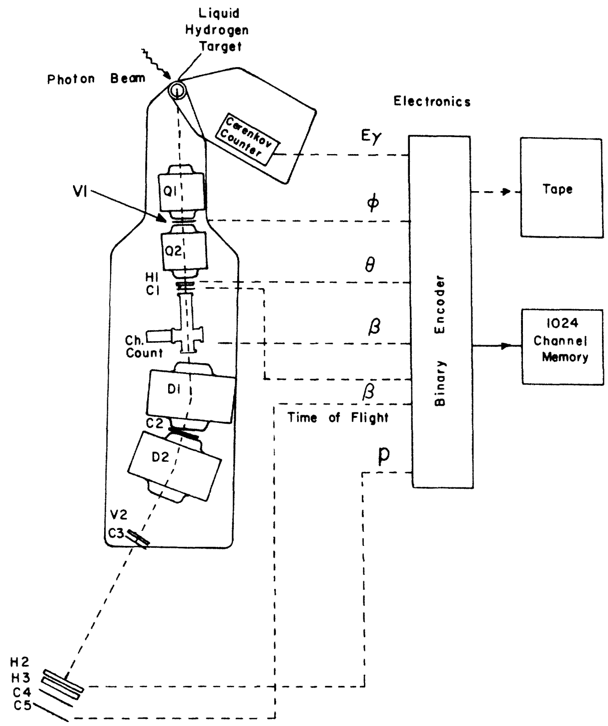

FIG. 1. Mechanical layout of the experiment and schematic of the electronics system. Q = quadrupole, D = deflecting magnet, H = horizontal hodoscope, V = vertical hodoscope, C = large counter.

which form a parallel beam, a differential Cherenkov counter, and two deflecting magnets ($D1$ and $D2$). Scintillator hodoscopes, $H1$, $H2$, $H3$ and $V1$, $V2$ measure displacements of the particle trajectory from the optic axis in the horizontal and vertical directions of the particle trajectory. Scintillation detectors $C1$ to $C5$ are used for triggering, checking, and time-of-flight measurement (from $C1$ to $C5$). We are able to use the information from the scintillators to measure the momentum (to $\pm\frac{1}{2}\%$ plus a scattering error varying from $\pm 1.5\%$ to $\pm 0.5\%$) within an accepted spread of 20%, the angle of emission ($\pm\frac{1}{4}°$), and the time of flight (± 2 nsec) of a particle. The second platform carries a tetrabromoethane total absorption gamma ray counter; its resolution is $\pm 10\%$ at 1 BeV; the aperture is variable (by moving the counter forward and backward).

The information for each event is converted to binary form and stored on punched paper tape for later analysis. A running total of events classified by momentum, angle, π, or proton velocity, with or without a gamma ray coincidence is kept for immediate inspection in the memory of a 1024-channel analyzer.

Our runs were taken such as to measure, primarily, the reaction

$$\gamma + p \to p + \pi^0$$

at 90° and 60° in the center-of-mass system for the pion. In each run the accelerator electron energy was set so that the maximum proton momentum was near the top of our momentum window. The beam intensity was monitored by a quantameter[1] whose absolute accuracy is estimated correct to $\pm 10\%$. The π^+ and γ-proton momentum cutoffs provide an energy intercalibration with the machine. The γ spectra from γ-proton coincidences show a peak and a minimum, as expected, giving an unambiguous cutoff point for π^0 events (Fig. 2). The efficiency of the γ-ray counter may be measured by taking the ratio of γ-proton to proton counts at the high-energy tip of the momentum curve. The measured efficiencies agree with our calculated expectations. Above a photon energy of 2 BeV our resolution is not sufficiently good to separate proton recoils from single and multiple π production; we then use calculated efficiencies. The spectrometer solid angle is obtained by normalizing to those events near the optic axis whose solid angle can be calculated in terms of hodoscope counter sizes independent of magnet parameters and physical stops.

We cannot kinematically separate the reaction $\gamma + p \to \gamma + p$ and it must be considered as included in our cross section. Where it has been measured[2] it is less than 10% of the π^0-p cross sections; this is reasonable considering the additional photon vertex. Multiple π^0 processes and

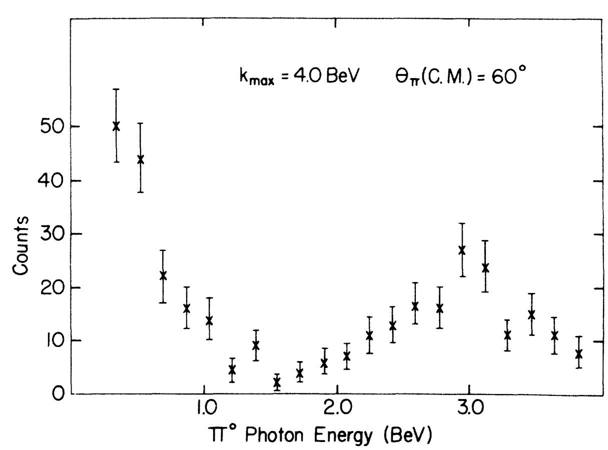

FIG. 2. Gamma-ray spectrum measured in the absorption Cherenkov counter in coincidence with the protons in the highest 6% momentum interval.

η^0 production tend to give a flat or decreasing γ-ray spectrum as opposed to the peaked spectrum observed (Fig. 2). As the electron energy is increased, thereby potentially increasing the number of multiparticle channels for a γ-proton coincidence of given energy and momentum, the counts in the single-π^0 peak do not increase within our statistics. From these observations we estimate a contribution of less than 20% from multiple pion or η^0 channels to our measured cross section (η^0 counting efficiency is about 10% to 20% of the π^0 efficiency over the energy range from 1.5 BeV to 4 BeV).

We have also measured π^+ cross sections concurrently; the single-π^+ momentum is distinguishable from the lower momenta of double-π photoproduction. The angle of measurement for the charged particle corresponds to 90° (c.m.) for the proton; therefore the π^+ (c.m.) angle of measurement varies with energy.

Our measured cross sections are presented in Fig. 3. Grossly, it is clear the differential cross section is decreasing. Superposed on this behavior are evident the "1.69"-BeV, $T=\frac{1}{2}$ (arrow a, Fig. 3) resonance and the "1.92"-BeV, $T=\frac{3}{2}$ (b) resonance observed in π scattering. Arrows also indicate the previously measured positions of the $T=\frac{1}{2}$, 2.19-BeV resonance[3] (c), the $T=\frac{3}{2}$, 2.36-BeV resonance (d), and a postulated $T=\frac{3}{2}$, 1.66-BeV "resonance" (e).[4] The presence of the two resonances of reference 3 appear as only unimportant shoulders, if anything, in the 90° cross section. However, in the 60° points there is a bump centered at mass = 2.25 BeV which could be this combination unresolved. These two resonances are also unresolved in the π^--p total cross section of reference 3. It is of interest to note that the 1.69-BeV resonance is very narrow in our 90° data and that the peak falls exactly at the value given by πp cross sections. Both phenomena would indicate that this resonance is not interfering with some other amplitude, such as the still large drop-off from the $T=\frac{1}{2}$, 1.51-BeV resonance below it. This would confirm that these two resonances are of opposite parity; they would then not interfere at 90°. This is in agreement with present conceptions.

The overall behavior of these photoproduction cross sections is one of rapid fall with energy

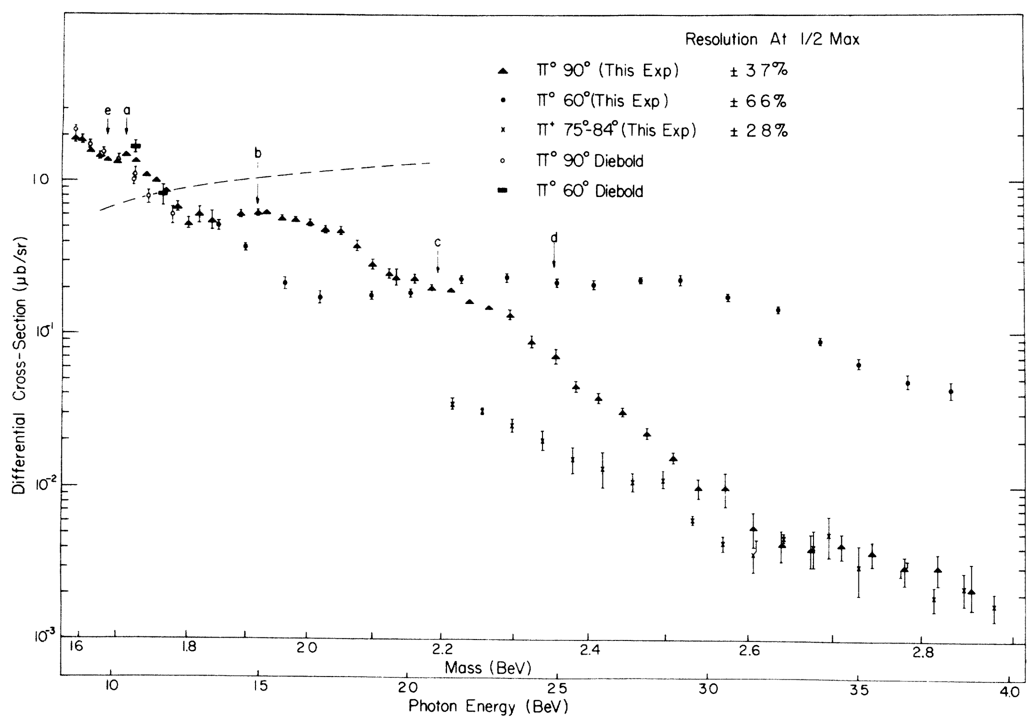

FIG. 3. Experimental results on photoproduction of π^0 and π^+ mesons. Shown at the lowest energies are points taken from Diebold [R. E. Diebold, Ph.D. thesis, California Institute of Technology, 1963 (unpublished); R. Diebold, R. Gomez, R. Talman, and R. L. Walker, Phys. Rev. Letters 7, 323 (1961)]. The dotted line refers to a field theoretic calculation assuming the exchange of a virtual ω_0; the line is normalized to a point measured by Talman et al. (reference 7) who fit their angular distribution to such a model.

and angle complicated by other structure or resonant amplitudes. In this connection, models of π photoproduction with an exchanged vector boson have been calculated.[5,6] Talman et al.[7] have fitted these to the π^0 photoproduction angular distribution at 1.14-BeV photon energy. We have calculated the expected energetic behavior from reference 6 (Fig. 3) and normalized it to their point at 1.14 BeV; this model involves the exchange of an ω_0. It is clear that the true cross section falls much faster; thus the need for form factors or their dynamic equivalent is evident at these momentum transfers for such a model.

We note also that the π^+ cross section is much smaller than the π^0 cross section. This could be explained if one still imagines the main nonresonant photoproduction amplitude as occurring through the exchange of a virtual $T=0$ particle or state, such as the ω^0. The near absence of a $T=1$ particle exchange, such as a virtual ρ, might be further evidence for the prohibition of a pure $\gamma\pi\rho$ vertex due to non-conservation of the proposed A quantum number,[8] whereas $\gamma\pi\omega^0$ is allowed.

We wish to thank D. Garelick, M. Fotino, W. Lobar, and C. Strumski for their invaluable aid during various phases of the experiment. In addition we thank T. Collins and G. Voss and the cooperative Cambridge Electron Accelerator staff whose work made this experiment possible.

---

*Work supported in part through funds provided by the U. S. Atomic Energy Commission under Contract No. AT(30-1)-2098.

†Part of this experiment is reported in greater detail in a Ph.D. thesis by Z. Bar-Yam, Massachusetts Institute of Technology (1962).

‡Laborati Nazionali di Frascati, Frascati (Roma), Italy

[1]R. R. Wilson, Nucl. Inst. 1, 101 (1957). This instrument had been indirectly intercalibrated at the Cornell Electron Synchrotron. In the latter part of our runs a change by a consistent factor of 1.85 occurred in our measured cross section, as could be seen from intercomparison of similar runs before and after the change. We have so corrected the later data to agree with our early runs.

[2]R. F. Streining, E. Loh, and M. Deutsch, Phys. Rev. Letters 10, 536 (1963); and other references included in this Letter.

[3]A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. Letters 10, 262 (1963).

[4]T. F. Kycia and K. F. Riley, Phys. Rev. Letters 10, 266 (1963).

[5]M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[6]M. J. Moravcsik, Phys. Rev. 125, 734 (1962).

[7]R. M. Talman, C. R. Clinesmith, R. Gomez, and A. V. Tollestrup, Phys. Rev. Letters 9, 177 (1962).

[8]J. Bronzan and F. Low, Phys. Rev. Letters 12, 522 (1964).

EVIDENCE FOR TWO NEW RESONANCES IN THE π-NUCLEON SYSTEM*†

R. Alvarez, Z. Bar-Yam, W. Kern, D. Luckey, L. S. Osborne, and S. Tazzari‡
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

and

R. Fessel
Cambridge Electron Accelerator, Cambridge, Massachusetts
(Received 2 April 1964)

Considerable structure is evident in the photoproduction cross section from 0.9 BeV up to 4 BeV (see Fig. 1).[1] Up to 2.5 BeV this structure can be understood in terms of previously observed resonances. The cross section is the square of the sum of a nonresonant and resonant (when present) amplitudes. The absolute amplitude of a high-J resonance is about the same at 60° and 90° yet it is clear that the cross sections we measure at 1.5 BeV and 2.3 BeV (where there are resonances of mass 1.92, 2.19, and 2.36 BeV)[2] are certainly not equal. Indeed, in the 1.92-BeV resonance at 60° it would appear that the resonant term subtracts from rather than adds to the nonresonant background. We may conclude that the nonresonant amplitudes dominate the photoproduction cross sections and must be responsible for the large drop in cross section from 60° to 90° at energies above 2.3 BeV.

Beyond the known resonances some structure persists. At 60° the cross section continues high beyond the known resonance at 2.5 BeV suggesting another resonance at 2.9 ± 0.1 BeV (this