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.

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

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[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.

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

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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

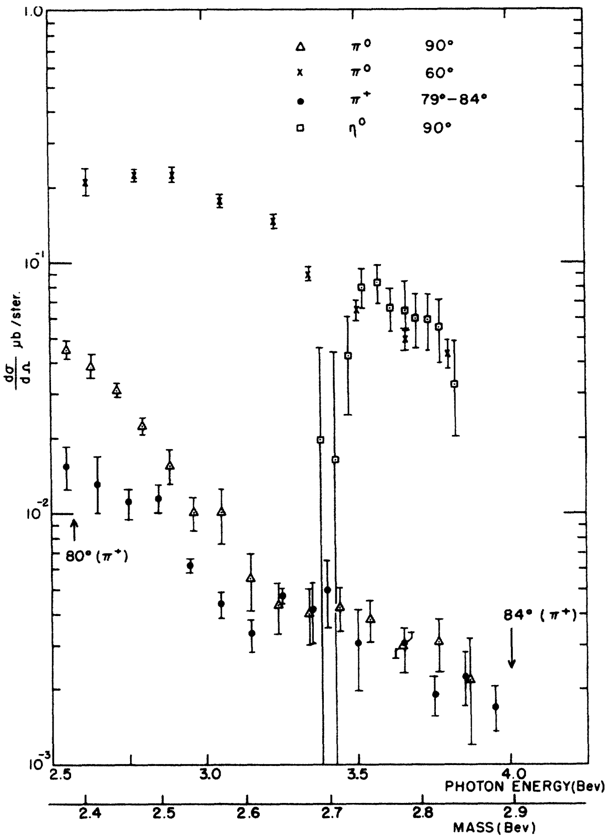

FIG. 1. Measured photoproduction cross-sections for π^+, π^0, π^0.

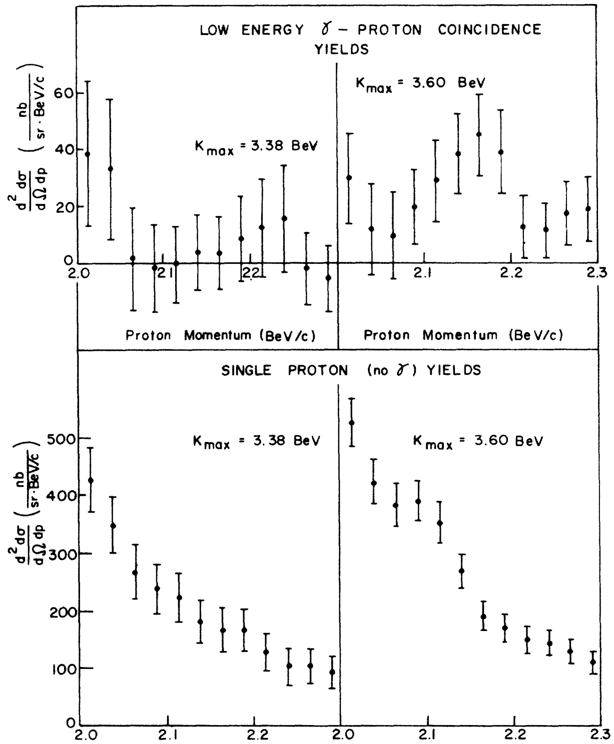

FIG. 2. Yields of single protons and proton-gamma ray coincidences. The gamma-ray energies detected are between 0.35 BeV and 1.0 BeV to avoid contribution from photoproduction. In both yields we obtain a "bump" when the maximum photon energy is increased from 3.38 BeV to 3.6 BeV.

corresponds to a mass of 2.52 ± 0.04 BeV). There is only a slight suggestion of this in the 90° π^0 data and in the π^+ data. Because of the larger π^0 cross sections one would guess that the predominant production mode is in the $T = \frac{3}{2}$ state; however, lack of knowledge of the non-resonant production prevents specifying the T state with certitude.

At a bombarding energy of 3.5 BeV there appears in the π^0 (90°) and π^+ data further evidence of some structure; it appears as "shoulders" in a rapidly dropping cross section. The effect is somewhat more pronounced in the π^+ cross section indicating that $T = \frac{1}{2}$ state may be dominant in this case. (The π^+ to π^0 amplitude ratio is $\sqrt{2}$ to 1 for $T = \frac{1}{2}$ and 1 to $\sqrt{2}$ for $T = \frac{3}{2}$.)

We also observed coincidences between protons and gamma rays lower in energy than those expected from π^0 production. The yield of these coincidences as a function of proton momentum is shown in Fig. 2(a) for two runs with bremsstrahlung cutoffs of 3.38 and 3.6 BeV, respectively, and shows a bump at 2.15 BeV/c at the higher photon energy. Thus the onset of this effect occurs at approximately 3.5 BeV. Shown in Fig. 2(b) is the yield of single protons (no gamma rays) for the same runs; there appears to be additional yield above a smooth curve at about the same proton momentum. Given this proton momentum and the photon energy associated with this yield we can solve for the effective mass of the particles produced with the protons; we obtain $m = 490 \pm 80$ MeV.

Looking at the ratio of single-proton events to γp events in the bumps at 2.15 BeV/c and assuming they arise from the same particle or particles, we obtain 3 ± 2 to 1; the gamma rays are in the energy range of 0.35 to 1.0 BeV to avoid contamination from the 2.0-BeV π^0. The large error comes from estimating the yield in the single-proton bump over a smooth background. For a particle of the mass observed, the percentage solid angle for its decay products subtended by our γ-ray counter is 8%; we require an average of more than three γ rays in the decay pro-

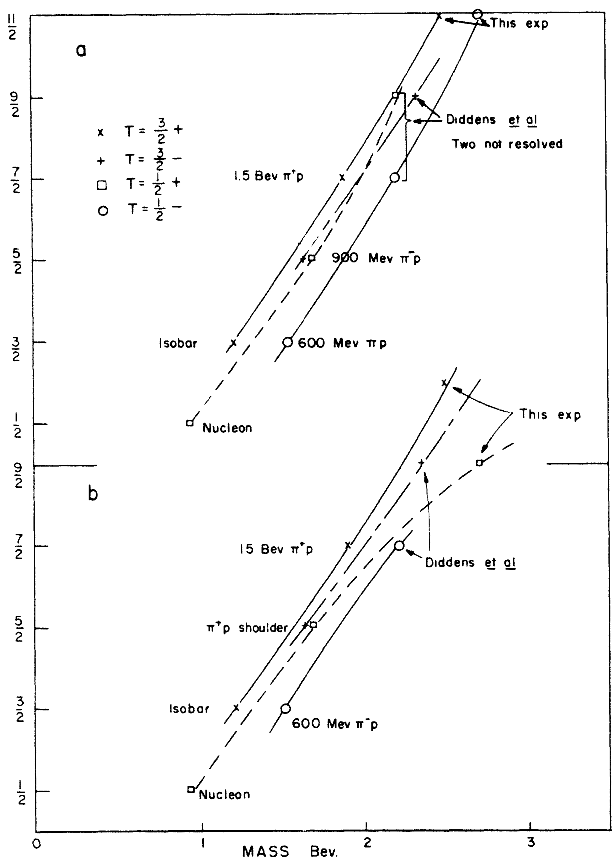

FIG. 3. Two possible Regge trajectory assignments.

ducts to obtain the measured ratio. This situation is true of an η^0, for which we compute an expected p to γp ratio of 5 which agrees with our observation. Essentially, a bump in the proton recoil spectrum (Fig. 2) from a continuous bombarding spectrum requires both a particle ("resonance") being produced and the production cross section going through a resonance. It seems reasonable that we are producing π^0's; this would confirm the original expectation from the π^+ ratio that this 3.5-BeV resonance is $T=\frac{1}{2}$, since the η^0 has $T=0$. Assuming an η^0 we have plotted its cross section in Fig. 1.

The cross section for η^0 production at the peak is 80 ± 10 nb compared to 3 ± 1.5 nb for π^+ and 2 ± 1.5 nb for π^0. Again the π cross sections are estimated by their rise above a rather ambiguous smooth background. For amusement we can compare this with the squares of the SU(3) Clebsch-Gordan coefficients[3] for the decay of a $T=\frac{1}{2}$, $Y=+1$ member of some representation into two members of two octets, in particular the π-nucleon and η-nucleon. Depending on the multiplet membership of the decaying resonance, we obtain for the $\eta^0:\pi^+:\pi^0$ ratio

for $\{27\}$, 27:2:1;

for $\{\overline{10}\}$, 3:2:1;

for $\{8_1\}$, 1:6:3;

for $\{8_2\}$, 3:2:1.

Thus the large η to π production ratio is explainable in SU(3) terms if the new resonance is a member of a $\{27\}$ representation. We assume that, with the decay energy so high, the η-π mass difference has little effect.[4]

The highest energy resonances have not been well enough measured in angular distribution or unambiguously analyzed to determine their J and parity. Nevertheless certain tentative J values and parity assignments have been given these resonances to fit them on Regge trajectories giving a smooth line and a resonance on each line spaced $\Delta J=2$ apart. We show in Fig. 3 two possible assignments for the resonances of this experiment. We assume that the 2.52-BeV resonance is $T=\frac{3}{2}$; it falls on a continuation of the "isobar" line. There seem to be two reasonable assignments for the 2.7-BeV ($T=\frac{1}{2}$) resonance depending upon how one assigns the 2.2-BeV resonance of Diddens et al. If the 2.7-BeV resonance lies on the nucleon line [Fig. 3(b)] the Regge trajectory bends downward; a continuation of this behavior would lead to increased spacing between resonances and, if the trajectory turns down sufficiently, an end to the resonances. If we choose the assignment of Fig. 3(a) we would postulate two $T=\frac{1}{2}$ resonances at about 2.2 BeV which might appear as one resonance. In this case the trajectories turn upward as the $T=\frac{3}{2}$ appears to do. A continuation of this behavior would suggest more resonances at higher energies with a decreasing spacing. These curves are closer to $J \sim M^2$ than $J \sim M$. Presumably the members of one trajectory belong to SU(3) representations of the same dimensionality; if the 2.7-BeV resonance is a member of a $\{27\}$ representation it would then be on a new trajectory.

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†Part of this experiment is reported in greater detail in a Ph. D. thesis by Z. Bar-Yam, M.I.T., 1962.

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[2]A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. Letters 10, 262 (1963).
[3]J. J. de Swart, Rev. Mod. Phys. 35, 916 (1963).
[4]It is possible to obtain an arbitrary η^0 to π ratio by taking a mixture of the two $\{8\}$ representations for the parent particle. This would require a near cancellation of the two $\{8\}$- representation matrix elements for the π mode of decay.

BROKEN SYMMETRIES AND MASSLESS PARTICLES*

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In a recent note Klein and Lee[1] have discussed the Goldstone theorem[2,3]: that any solution of a Lorentz-invariant theory that violates an internal symmetry operation of that theory will contain a massless scalar particle. They showed that this theorem does not necessarily apply in nonrelativistic theories and they implied that their work cast doubt upon the original theorem. In this they were mistaken. The theorem fails, trivially, in the nonrelativistic case for reasons which cannot affect the relativistic version.

Relativistic theories.—The Goldstone theorem can be deduced from the behavior of the generator of the internal symmetry. Since this generator is related to a conserved four-vector current, we can gain enough information about the structure of the Fourier transform of a commutator of the conserved current with field quantities to prove the theorem. If the symmetry operation yields a conserved current, j_μ, such that

$$i[\int d^3x\, j_0(x), \varphi_1(y)] = \varphi_2(y) \qquad (1)$$

is part of the statement of the symmetry operation, where φ_1 and φ_2 are scalar or pseudoscalar quantities formed from the field operators (there is an appropriate relationship changing φ_2 into φ_1), and the violation of symmetry in the solution is that the vacuum expectation value of φ_2 shall not vanish, then

$$i\langle[\int d^3x\, j_0(x), \varphi_1(y)]\rangle = \langle\varphi_2(0)\rangle \neq 0. \qquad (2)$$

We may write the most general form for the structure of the Fourier transform of the vacuum expectation of the commutator of j_μ with φ as

$$\text{F.T.} = i\int dx\, e^{ikx}\langle[j_\mu(x), \varphi_1(0)]\rangle$$
$$= \epsilon(k_0)k_\mu\rho_1(k^2) + k_\mu\rho_2(k^2). \qquad (3)$$

k_μ occurs because the commutator must be a four-vector. In the structure (3), k_μ is actually the total energy-momentum of the intermediate states that would arise in an expansion of the left-hand side. k_μ must be timelike. The conservation law, $\partial_\mu j^\mu = 0$, requires

$$\epsilon(k_0)k^2\rho_1 + k^2\rho_2 \equiv 0 \text{ for all } k_\mu$$

and therefore

$$\rho_1 = C_1\delta(k^2), \quad \rho_2 = C_2\delta(k^2). \qquad (4)$$

Thus, in the relativistic case, the Fourier transform of this commutator must be proportional to $\delta(k^2)$. Such a δ function rises only from a massless intermediate state. The broken symmetry condition (2) states that the weight constant, C_1, is nonvanishing, since

$$C_1/2\pi = \langle\varphi_2\rangle \neq 0.$$

There must arise, in the complete set of intermediate states, massless particle states with the quantum numbers of j_μ and φ_1.

Nonrelativistic theories.—We can imbed a nonrelativistic theory in a covariant framework by introducing an external timelike vector, n_μ [which we will take as $(1,0,0,0)$]. Then the general form of the Fourier transform of Eq. (3) becomes

$$\text{F.T.} = k_\mu\rho_1(k^2, nk) + n_\mu\rho_2(k^2, nk) + C_3 n_\mu \delta^4(k) \qquad (5)$$

in which we no longer need the $\epsilon(k_0)$ if we take the ρ's to be arbitrary functions of nk. The conservation condition now relates the ρ's and yields for (5)

$$\text{F.T.} = k_\mu\delta(k^2)\rho_4(nk)$$
$$+[k^2 n_\mu - k_\mu(nk)]\rho_5(k^2, nk) + C_3 n_\mu\delta^4(k) \qquad (6)$$

as the general structure transverse to k_μ.

Now if we specialize to the commutator of the integral of j_0 with φ_1, each term can contribute