The 600μ nuclear emulsions of type Ilford G5 were developed by the temperature development method so as to permit an easy detection of the highest energy protons (120 Mev) produced in the photomeson process. The scanning was systematic and with less than 3 percent loss. For each track in a total of 1080 found in an area of 6.7 cm^2, the angle with the gamma-ray beam was measured and the energy was calculated from the total range in the successive emulsions of the stack and in the gas. The reaction being a two-body process, the conservation laws enable one to calculate from these data (and from the known value of the π^0 rest mass) the center-of-mass angle and momentum of the π^0 meson together with the energy of the incident photon. The error of each individual track is evaluated to be $\pm 5°$ in angle and ± 10 Mev in γ-ray energy.

The occurrence of background proton tracks was detected by examining the region of angles and energies where photomesons are not emitted. Their intensity and angular distribution[1] identified them as coming from γ, p reactions in the 0.5 percent (by volume) oxygen and nitrogen impurities in the hydrogen gas. By extrapolation, using the measured angular distribution,[2] they were found to amount to about 10 percent of the tracks in the region where the photomeson protons are found, and subtracted out. Similarly, all other sources of background could be ruled out, including the proton Compton effect for which an upper limit of the cross section can be set at 5 ± 5 percent of the neutral meson cross section. The theoretical estimate is, of course, even smaller.

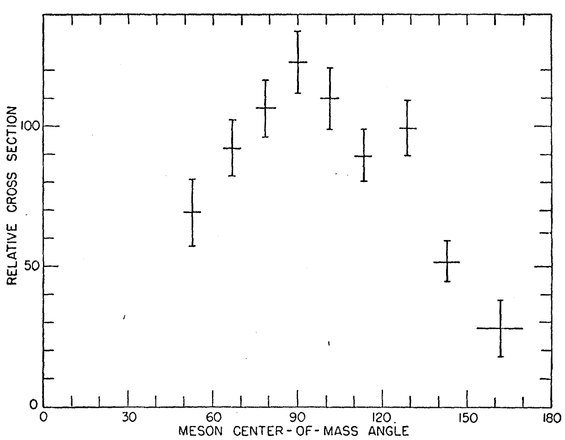

FIG. 2. Center-of-mass angular distribution for the production of neutral mesons on hydrogen by γ-rays from the bremsstrahlung of 320-Mev electrons. The forward angles correspond to protons stopped by the hydrogen gas, and cannot be observed in this experiment.

The excitation curve is given by Fig. 1 *versus* the quantity p^3k, where p and k are the momentum of the meson and the gamma-ray, respectively, in the center-of-mass frame. In computing these data, the bremsstrahlung spectrum was calculated by the Heitler formula and corrected for absorption along the beam and for the finite energy resolution of the measurements. The angular distribution in the center-of-mass frame is shown by Fig. 2. It is found to be symmetrical with respect to $90\pm 2°$. When examined separately in the low and high energy region, the angular distribution retains this symmetry. The best fit to an $a+b\sin^2\theta$ law gives $b/a=5\pm 3$.

The threshold of the reaction is found by extrapolating the excitation curve to zero. From its value, the rest mass of the π^0 meson can be calculated and it should match with the value used for the laboratory to center-of-mass transformation. Doing this transformation with various assumptions on the π^0 rest mass, the best match was found for $m_{\pi^0}=130\pm 10$ Mev. This measurement of the π^0 rest mass is not free from rather arbitrary assumptions, it would not hold for instance if the excitation curve plotted against p^3k showed an appreciable curvature in the low energy region.[3]

Our results are, on the whole, not inconsistent with those obtained by other methods.[4-6] They are in good agreement with the phenomenological theory of Brueckner and Watson[3] based on the existence of an intermediate excited state of the nucleon with spin $\frac{3}{2}$ and isotopic spin $\frac{3}{2}$ which predicts a $1+1.5\sin^2\theta$ angular distribution and a p^3k excitation curve near threshold. They seem to disagree with the predictions of the perturbation approximation.[7] The symmetry of the angular distribution with respect to 90° is interpreted as an indication of a very small effect of the nucleon recoil. It was pointed out to us by Feld[8] that both a p^3k excitation curve and a $1+1.5\sin^2\theta$ angular distribution can be deduced from conservation laws assuming a pseudoscalar π^0 meson, a magnetic dipole interaction of the gamma-ray, and an intermediate state of the nucleon with spin $\frac{3}{2}$ (no assumption on the isotopic spin).

In an attempt to observe a resonance in the excitation curve[3] a new exposure was taken at higher synchrotron energy. The scanning of the plates is in progress.

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† Now with the Texas Company, Geophysical Laboratory, Bellaire, Texas.

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The Angular and Energy Distributions in Photomeson Production*

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THE experiments[1] on the production of neutral π-mesons by the reaction $\gamma+p\rightarrow p+\pi^0$, as well as the known features of positive π-meson photoproduction, appear to be describable in terms of a phenomenological (isobar) theory as developed by Brueckner and Watson.[2] However, since their theory adopts certain features of various meson field theories, it is of interest to consider the extent to which it may be possible to extract from the experimental information those aspects which are independent of any special meson theory. It must be emphasized in advance that all of the results of the following considerations are contained, either implicitly or explicitly, in the paper of Brueckner and Watson. It is perhaps worth while, however, to restate some of their results in a different form which may help to emphasize the general character of the conclusions and to highlight their physical significance.

In particular, as is well known, it can easily be demonstrated by the methods first developed by Hamilton[3] that, provided a reaction goes through an intermediate state of definite angular momentum, the angular distribution of the reaction products is independent of most of the specific features of the interaction. Let us consider the reaction $\gamma+p\rightarrow p+\pi^0$. Suppose that the proton absorbs a magnetic-dipole γ-ray ($l_\gamma=1$, no parity change) and goes to an intermediate state of $J=\frac{3}{2}+$. (The positive parity is with respect to the parity of the proton.) The decay of the intermediate state, to a proton and π^0 meson, requires that the meson be in a p-state ($l_\pi=1$), since the π-meson is known to have negative parity with respect to the proton (pseudoscalar) and since the next highest possible value of l_π, three units of angular momentum, could not lead to the $j=\frac{1}{2}$ of the proton from a state of $J=\frac{3}{2}+$. Following the method of Hamilton, which permits the angular distribution to be expressed in terms of the most general quantum-mechanical features of angular momentum vectors, we take the incident γ-ray to define the z axis. The angular distribution of the reaction is then given by

$$W(\theta)=\sum_{m_i}\sum_{m_\pi}\sum_{m_\gamma}|a(j_il_\gamma;J;j_fl_\pi)\times(j_i,m_i;l_\gamma,m_\gamma|j_i,l_\gamma;J,m=m_i+m_\gamma)\mathfrak{D}_{l_\gamma}{}^{m_\gamma}(0)\times(j_f,l_\pi;J,m/j_f,m-m_\pi;l_\pi,m_\pi)Y_{l_\pi}{}^m(\theta,\varphi)|^2,\quad(1)$$

where a is the matrix element (amplitude) for the reaction; $\mathfrak{D}$ and Y are the vector and ordinary spherical harmonics, respectively; $j_i=\frac{1}{2}$, m_i represents the initial proton state, $j_f=\frac{1}{2}$, m_f the final proton state, J, m the intermediate state angular momentum quantum numbers; and $(j_1,m_1,j_2,m_2/j_1,j_2;J,m=m_1+m_2)$ are the Clebsch-Gordon coefficients, tabulated by Condon and Shortley.[4] These calculations have been carried out for a number of possibilities and the results are given in Table I. Also given in the last column of Table I is the expected dependence of the cross section, or $|a|^2$, near threshold on the momentum, p, of the π-meson in the c.m. system (i.e., neglecting the dependence on γ-ray energy). An interesting feature of the above results is that $W(\theta)$ depends only on the values of J and l_γ. This is easily understood if one considers the inverse process; an incident π-meson along the z axis cannot alter the m-value of the system and therefore, irrespective of the value of l_π, leads always to the same intermediate states.

TABLE I. Angular and energy distributions in the photoproduction of π-mesons on nucleons.

γ-ray absorbed	Intermediate state	l of π-meson	$W(\theta)$	π-momentum dependence
Mag. dipole	1/2+	1	constant	p^3
Mag. dipole	3/2+	1	$2+3\sin^2\theta$	p^3
Elect. dipole	1/2−	0	constant	p
Elect. dipole	3/2−	2	$2+3\sin^2\theta$	p^5
Elect. quad.	3/2+	1	$1+\cos^2\theta$	p^3
Elect. quad.	5/2+	3	$1+6\cos^2\theta-5\cos^4\theta$	p^7

The ambiguity can, of course, be resolved by an observation of the energy dependence of the cross section near threshold. In the case of π^0 production, this turns out experimentally to be $\propto p^3$ of the meson (in the c.m. system) which, taken together with the angular distribution, indicates that the process is magnetic dipole absorption to a $J=\frac{3}{2}+$ intermediate state. In the case of π^+ production there is, however, strong indication of a first power p-dependence near threshold, which requires electric dipole absorption to a $\frac{1}{2}-$ intermediate state.

As can be seen from Table I, there are a variety of possible reactions, even if we confine ourselves to dipole-absorption processes. Furthermore, if more than one of these processes occurs in the same reaction, it is possible to have interference effects.[5] We confine our attention to two possibilities only: magnetic dipole absorption to $J=\frac{3}{2}+$, and electric dipole absorption to $J=\frac{1}{2}-$. The expected angular distribution is, then,

$$W(\theta)=|a|^2+2\,\mathrm{Re}(ab^*)\cos\theta+\tfrac{1}{2}|b|^2(2+3\sin^2\theta),\quad(2)$$

where b and a are, respectively, the amplitudes for the two processes.[6]

Now, the above analysis appears, at first sight, not to allow for the experimentally observed difference between π^0 and π^+ production on protons, since angular momentum considerations alone do not distinguish between the charge states of the meson and nucleon. Here, we can invoke the assumption of charge independence which introduces an additional quantum number into the system—the isotopic spin. The two reactions,

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

and

$$\gamma+p\rightarrow n+\pi^+,$$

differ only in the relative amplitudes of the final state wave function in the isotopic spin $\frac{3}{2}$ and $\frac{1}{2}$ components. In general, the reaction amplitudes are

$$a_J(\pi^0)=(\sqrt{\tfrac{2}{3}})a_{J,\,T=\frac{3}{2}}+(\sqrt{\tfrac{1}{3}})a_{J,\,T=\frac{1}{2}}\quad(3a)$$

for the first reaction, and

$$a_J(\pi^+)=(\sqrt{\tfrac{1}{3}})a_{J,\frac{3}{2}}-(\sqrt{\tfrac{2}{3}})a_{J,\frac{1}{2}}\quad(3b)$$

for the second. Following Brueckner and Watson,[2] we can choose $\sqrt{2}a_{\frac{1}{2},\frac{3}{2}}=-a_{\frac{1}{2},\frac{1}{2}}$. With this choice (made only on the basis of the experimental evidence on π^0 production), the dipole-absorption and the interference terms vanish for the π^0 process, but remain for the π^+ process. We are still left with two arbitrary amplitudes for the magnetic-dipole process, i.e., $a_{\frac{3}{2},\frac{3}{2}}$ and $a_{\frac{3}{2},\frac{1}{2}}$. There is, on the basis of the present photomeson experiments, no way of choosing these. However, the evidence from π-meson scattering on hydrogen has been interpreted[7] as indicating that $a_{\frac{3}{2},\frac{3}{2}}\gg a_{\frac{3}{2},\frac{1}{2}}$. The relative values of these two constants could also be obtained from a comparison of the cross sections for those parts of the π^0 and π^+ photoproduction reactions corresponding to magnetic-dipole absorption (the $2+3\sin^2\theta$ terms). In particular, for the assumption of $T=\frac{3}{2}$ production only, the π^0 cross section would be twice as great as the π^+ cross section.

While the evidence is as yet by no means conclusive, the results on π^0 production taken together with the relative magnitudes of the $\pi^\pm$ scattering processes are suggestive of a resonance corresponding to a proton "isobar" state of angular momentum $\frac{3}{2}$ in both ordinary and isotopic spin space.[2,7] However, the shape of the π^0 photoexcitation cross section is not well enough known to permit an evaluation of the "isobar resonance" constants. Further measurements, both on photoproduction and scattering, with improved accuracy and extended energy range, are required before an unambiguous answer can be given to the questions of the existence and properties of the isobar.

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[1] See preceding letter by Goldschmidt-Clermont, Osborne, and Scott [Phys. Rev. **89**, 329 (1953)] which also contains references to other experiments.

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[5] $W(\theta)$ is now computed by an additional summation, in Eq. (1), taken inside the absolute value signs and over the possible intermediate J-values.

[6] It is also possible to include terms corresponding to magnetic dipole absorption to a $J=\frac{1}{2}+$ state, which gives rise to an interference term $\propto(3\cos^2\theta-1)/2$ which, however, does not lead to any asymmetry about 90° and which is not needed for the interpretation of the experiments now available.

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Infrared Photoconductivity Due to Neutral Impurities in Silicon

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IMPURITY photoconductivity has been observed in silicon at liquid helium temperatures out to 38 microns. The regions of impurity photoconductivity and intrinsic photoconductivity are well separated so that it is possible to make an unambiguous interpretation of the data. The results, moreover, enable one to obtain information about the ionization energies of impurities and clearly demonstrate the value of optical measurements in the study of impurity levels in semiconductors.

Optical data obtained at liquid nitrogen temperature over the range 2 to 25 microns have previously demonstrated the absorption by neutral impurities in n- and p-type silicon involving the photoionization of bound charge carriers.[1] Efforts to detect