We now write (it being supposed that the appropriate spin and polarization averages have been performed)

$$2\pi\rho_f|N_l|^2=(d\sigma_f/d\Omega)\eta, \tag{8}$$

where $d\sigma_f/d\Omega$ is the corresponding free nucleon cross section averaged over neutrons and protons in the nucleus. η is a factor which accounts for the modification of the free particle cross sections due to nuclear binding effects. Replacing the Σ_l by A, Eq. (7) becomes

$$\frac{d\sigma_\pi}{d\Omega}=\left(\frac{d\sigma_f}{d\Omega}\eta\frac{A}{V_A}\right)\int|\varphi_{-q}(\mathbf{x})|^2\rho(\mathbf{x})d^3x. \tag{9}$$

We do not expect η to show any pronounced A-dependence, so we consider it to be just a constant parameter (presumably $0<\eta<1$).

To find the absorption cross section, we use the meson continuity equation,

$$\nabla\cdot\mathbf{j}+\partial P/\partial t=-2(\mathrm{Im}V)P, \tag{10}$$

where $P=|\varphi_q(\mathbf{z})|^2$ is the meson density. The term on the right represents the absorption rate per unit volume. Integration over

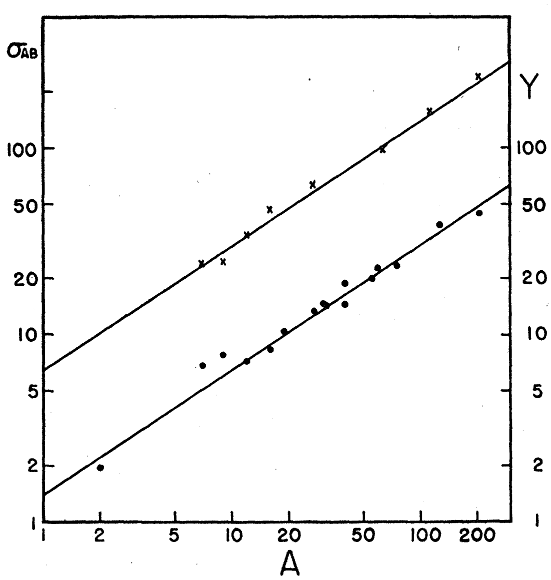

FIG. 1. The circles and x's represent charged meson photoproduction (see reference 2) and π^- absorption (see reference 4) cross sections, respectively. The straight line in each case is the A^1 law. The charged photoproduction yield Y is normalized to give 1.04 for the hydrogen yield, and the absolute absorption cross section may be obtained by multiplying σ_{AB} by 10^{-26} cm^2.

the nuclear volume gives the total absorption rate W.[9] The imaginary part of V is obtained from Eq. (1), so the absorption cross section is

$$\sigma_{AB}=\frac{W}{v_\pi}=\frac{1}{\lambda}\int|\varphi_q(\mathbf{z})|^2\rho(\mathbf{z})d^3z. \tag{11}$$

Since the integrals of Eqs. (9) and (11) are independent of the direction of $\mathbf{q}$, we obtain, by eliminating the integral from these equations,

$$\frac{d\sigma_\pi}{d\Omega}=\left(\frac{d\sigma_f}{d\Omega}\eta\lambda\frac{A}{V_A}\right)\sigma_{AB}, \tag{12}$$

where (by our assumption that η is independent of A) the only A-dependence comes from σ_{AB}. Equation (12) permits comparison of the photoproduction and absorption experiments without detailed calculation.

The experimental measurement[4] of σ_{AB} included both absorption and inelastic scattering, whereas Littauer and Walker measure all emitted charged mesons at a given angle and energy. Energy-momentum considerations and the observation that absorption seems to predominate over inelastic scatterings at the energies considered imply that no very serious error is involved through the use of Eq. (12) to compare the two experiments.

In Fig. 1 the A-dependence of the photoproduction[2] of 50–80 Mev charged π-mesons and the absorption[4] of 85-Mev π^- mesons are compared. Both the photoproduction and the absorption are seen to have approximately the same A-dependence in agreement with Eq. (12). Inserting $(d\sigma_\pi/d\Omega)$, $(d\sigma_f/d\Omega)$, and σ_{AB} obtained from Fig. 1, we obtain

$$\lambda\eta=2.6\times10^{-13}\text{ cm}.$$

If the interaction mean free path in nuclei, λ, is 10^{-12} cm, $\eta=0.26$; if $\lambda=0.5\times10^{-12}$ cm, $\eta=0.52$. These values of η are reasonable and indicate that Eq. (12) is in satisfactory agreement with experiment.

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[8] Equation (6) is of the usual form for transition rates using first-order perturbation theory. A more detailed analysis using multiple scattering theory leads to this result and to Eq. (9) [see K. M. Watson, Phys. Rev. 88, 1163 (1952)].
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Photoproduction of Neutral Mesons in Hydrogen*

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THE photoproduction of neutral mesons in hydrogen has been investigated by observing the recoil protons in nuclear emulsions.

The gamma-ray beam from the MIT synchrotron, operating at 320 Mev, was passed along the axis of a cylindrical chamber containing hydrogen at 655 psi and $-60°$C. The beam entered and left the chamber through thin aluminum windows. Eight stacks of five nuclear emulsions, each 600μ thick, were held in position halfway along the chamber on a suitable holder, and were protected against the electromagnetic background originating in the windows by lead collimators. The geometry allowed protons making an angle of more than 8° with the beam to be recorded in the emulsion stacks. The lowest energy protons could not be observed because of the stopping power of the gas.

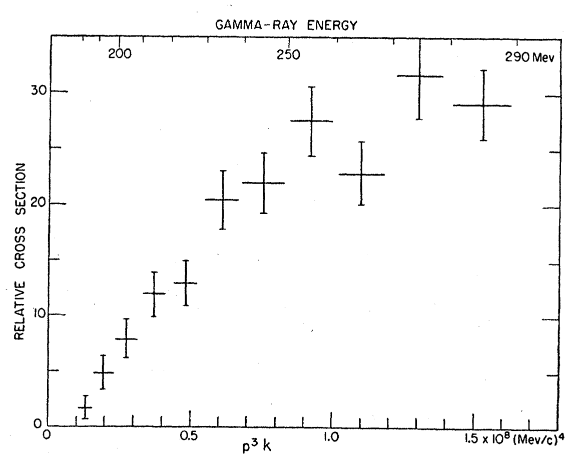

FIG. 1. Photoproduction of neutral mesons on hydrogen. Excitation curve for the emission of the neutral meson between 53° and 143° in the center-of-mass frame. The curve is expected to be proportional to p^3k in the low energy region for emission of the meson in a P state.

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.

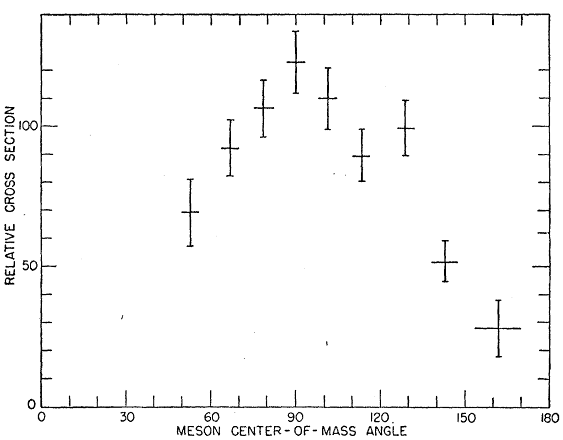

FIG. 2. Center-of-mass angular distribution for the production of neutral mesons on hydrogen by γ-rays from the bremsstrahlung of 320-Mev electrons. The forward angles correspond to protons stopped by the hydrogen gas, and cannot be observed in this experiment.

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