

entering into a delayed coincidence. The stability of the detecting system depends on the sensitivity of the meson counting rate to the minimum amplitudes required of the pulses. Such a plateau curve (counting rate vs. minimum pulse amplitude) is shown in Fig. 3.

With a synchrotron beam intensity of about 10^{10} Mev/sec. and the geometry of Fig. 1, a target of 4 g/cm² of carbon, and 1 in. of aluminum absorber, corresponding to a meson energy of 54 Mev, the meson counting rate is about 15 counts/min. This makes it possible to do experiments more quickly than with photographic emulsions. On the other hand, only positive mesons can be counted in this manner, and absolute cross-section measurements have a large error, since the detection efficiency is not known with precision.

We should like to express our thanks to Professor E. McMillan for his support of this research, and to the operating crew of the synchrotron, especially to Mr. W. Gibbins, for their able cooperation.

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¹ F. Rasetti, Phys. Rev. **60**, 198 (1941).

² Alvarez, Longacre, Ogren, and Thomas, Phys. Rev. **77**, 752 (1950).

Preliminary Results on the Production of Mesons by Photons on Carbon and Hydrogen*

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THE method of meson detection described in the preceding letter¹ is being applied to the study of the production of positive mesons by x-rays on hydrogen and heavier nuclei. We report here some preliminary results in which the hydrogen cross sections are obtained by subtracting the yields on carbon from those on paraffin. All the measurements reported here are being continued, and hydrogen cross section measurements with a liquid hydrogen target are in progress.

In interpreting these results it should be kept in mind that both energy and angle of production of the meson are measured, and these determine the incident x-ray energy by momentum and energy conservation in the case of production on hydrogen. This means, for instance, that a knowledge of the energy distribution of the mesons at a fixed angle of production and of the energy

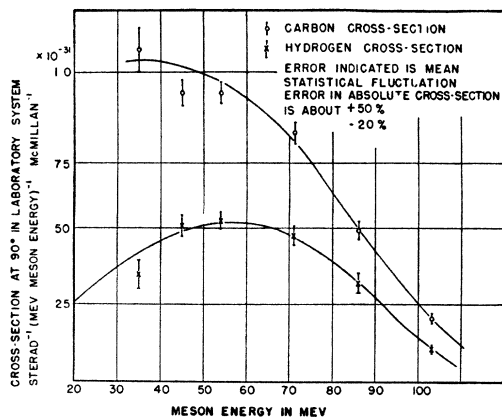


FIG. 1. Production of mesons by photons on carbon and hydrogen at 90°. The photons have a bremsstrahlung spectrum with a 330-Mev maximum energy. The number of McMILLANs in a bremsstrahlung beam is defined as the total energy in the beam divided by the maximum photon energy.

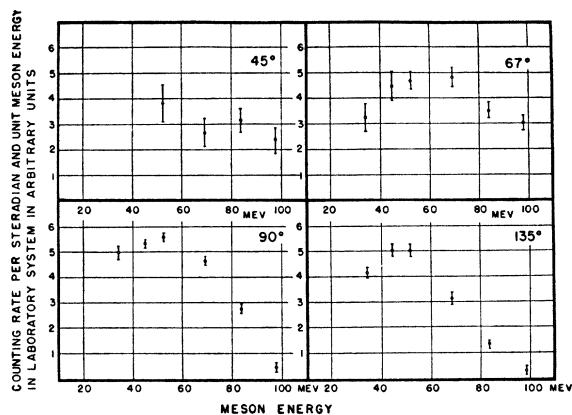


FIG. 2. The production of mesons in C₁₂H₁₄ at various angles as a function of the meson energy.

distribution of the incident x-ray beam allows a determination of the excitation function for photo-meson production. We feel however that the energy, angular and statistical accuracies of the data reported here do not yet warrant such an analysis.

Figure 1 shows the relative number of mesons produced by carbon atoms and hydrogen atoms at 90° in the laboratory system as a function of energy. The incident photons have a bremsstrahlung spectrum of 330-Mev maximum energy. The meson energy is determined from the energy-range relationship, and it is assumed that the nuclear absorption of mesons is zero.² The carbon cross sections have already been determined by photographic detection methods,³ and the two results agree within the statistical inaccuracies. The most startling fact shown in Fig. 1 (and also in Fig. 3) is that the cross section of the six bound protons in a carbon atom is only about twice as large as that of a single free proton. It is perhaps surprising that the effects of nuclear binding are so pronounced. However, a more detailed analysis⁴ shows that since the energy of the recoil nucleons is not very much greater than the Fermi energy, this inhibition of the reaction in the case of complex nuclei may be no more than a manifestation of the exclusion principle.

Figure 2 shows an attempt at obtaining similar information at several other angles. However, the statistical accuracies are not great enough to make the subtraction meaningful. So the data

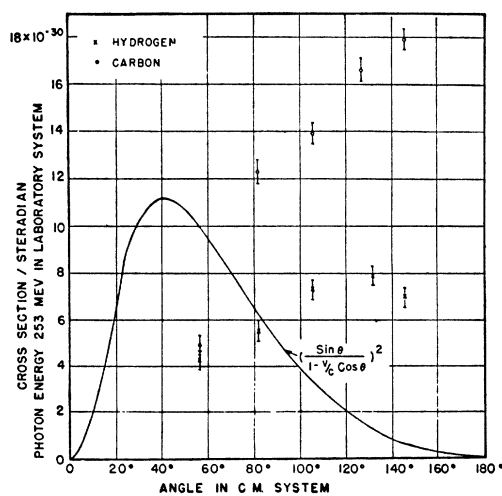


FIG. 3. The angular distribution of the mesons produced by 250-Mev (laboratory system) photons on hydrogen and carbon. The theoretical curve is that for an electric dipole photo-effect, $[\sin \theta / (1 - (v/c) \cos \theta)]^2$.

are added, instead of subtracted, and the points represent the production by a molecule of composition C_7H_{14} . The interesting thing here is that the cross sections are fairly independent of angle. This is shown again in Fig. 3. Here the cross sections are shown for five angles. At each angle a different amount of absorber is used, so that for hydrogen the photon energy at all angles is unique, 253 Mev. For the carbon points the analysis has been carried through in the same way, although in this case the binding of the nucleons makes the momentum and energy conservation arguments invalid. The cross sections have been plotted in absolute units; however, the error in the absolute value may be quite large. The errors indicated are the statistical errors, and represent the likely errors in the relative values. The theoretical curve in Fig. 3 is a plot of the function $\{\sin\theta/[I-(v/c)\cos\theta]\}^2$, the angular distribution of a simple electric dipole photo-effect. It is also substantially the prediction of the scalar meson theory.⁵ It can be seen that the actual distribution is quite incompatible with this, in fact the only theories which predict such a flat distribution are those in which the electromagnetic interaction is chiefly with the magnetic moment of the nucleons rather than the electric charge of the meson. This is so for the pseudoscalar meson theory with both types of coupling.⁶ However, the same theories which, because of the tight coupling of the mesons to the magnetic moment of the nucleon, predict a flat angular distribution, also predict nuclear radii of the dimensions of the Compton wavelength of the nucleons and can therefore hardly be taken seriously. On the one hand, the theories which predict a different distribution cannot be rejected because there remains the possibility, though small, that the disagreement is caused by the fact that the calculations are incorrect because relativity and the largeness of the coupling constant are not simultaneously taken into account. On the other hand, those theories which predict the observed result disagree violently with experiment in the nuclear force problem. It seems, therefore, impossible to make a meaningful comparison of the experiment with existing theory.

We wish to thank Professor E. McMillan for his support, Professor R. Serber for theoretical discussions, and Mr. Gibbins and the synchrotron crew for their assistance.

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¹ J. Steinberger and A. S. Bishop, Phys. Rev. **78**, 494 (1950).

² If, instead, the nuclear mean free path of mesons in aluminum were 200 g/cm², this would mean that the 100-Mev points would be too low by about 15 percent; lower energies would have proportionately smaller errors.

³ McMillan, Peterson, and White, Science **110**, 579 (1949).

⁴ The calculations for helium targets have been made by G. Chew and H. Lewis. They show that one may easily account for a σ (free proton)/ σ (bound proton) = 3, but it is not possible to make an accurate prediction of the expected effect. We wish to express our thanks to the authors for permission to quote their results before publication.

⁵ In the scalar theory this result is obtained in relativistic perturbation theory, and also rigorously without expansion in g if the nucleons are assumed to have infinite mass. We are indebted to Drs. K. M. Case and K. Watson who have independently obtained this result.

⁶ The perturbation theoretical results have been obtained by H. Feshbach and M. Lax, Phys. Rev. **76**, 134 (1949) and more completely by K. Brueckner (to be published).

Proton-Proton Scattering in Charged Scalar Theory*

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THE recent measurements by the Berkeley experimentalists¹ of 345-Mev proton-proton and 280-Mev neutron-proton scattering have shown a remarkable difference in the two types of scattering. The neutron-proton scattering has a cross section of 36 millibarns and is very strongly peaked at 0° and 180° in the center-of-mass system; the proton-proton scattering has a much larger differential cross section at 90 degrees and is nearly isotropic in the angular range 20 to 160 degrees.

An immediate qualitative explanation of these differences is

obtained by assuming that neutron-proton scattering takes place in lowest order through the exchange of single charged mesons, while proton-proton scattering in the lowest order occurs only through the exchange of pairs of charged mesons. This is equivalent to assuming that protons are coupled directly only to positive mesons.² If the calculations of Watson and Lepore³ on the radiative corrections to nuclear forces for pseudoscalar theory are considered in this hypothesis, it is found that not even rough qualitative agreement can be obtained with the experimental results. We therefore have calculated the neutron-proton and proton-proton scattering to fourth order in the meson nucleon coupling, using charged scalar theory.

It is found that the only important contributions to the fourth-order processes come from the exchange of two mesons. Terms corresponding to the polarization of the vacuum by the mesons give negligible contributions. The resulting fourth-order contribution to the S -matrix, ignoring corrections of order v^2/c^2 , which are less than 10 percent, is

$$M_4(P\bar{P}) = i(f/2\pi)^4 (V_{PP^4} - \text{exchange term}), \quad (1)$$

where

$$V_{PP^4} = \frac{1}{M^2} \int_0^1 dx \int_0^x dy \frac{4y}{[y^2 + (1-y)\rho + (1-x)(x-y)\theta]^2} \quad (2)$$

and

$$\rho = \mu^2/M^2, \quad \theta = (\mathbf{P} - \mathbf{P}')^2/M^2C^2.$$

The contribution to $N-P$ scattering in the fourth-order is very similar to that given by Eq. (1). It is apparent that since these matrix elements depend only on the momentum transfer, they can be expressed in a coordinate representation as purely static potentials. It is interesting to observe that the $P-P$ scattering given by (1) is almost exactly equivalent to that given by the Born approximation applied to the static Yukawa potential⁴

$$-(f/2\pi)^4 (11.15/4\pi) (e^{-kr}/r),$$

where

$$k = 2.80\mu c/\hbar = 0.207 \times 10^{-14} \text{ cm}^{-1}.$$

The differential cross section at 180 Mev for the $N-P$ scattering including the second-order contribution, and for the $P-P$ scattering are given in Fig. 1. Corrections of order v^2/c^2 have been included. It is apparent that the inclusion of the fourth-order $N-P$ scattering tends to reduce the asymmetry of the $N-P$ scattering about 90 degrees, and that the $P-P$ scattering is much less strongly peaked at 180 degrees than the $N-P$ scattering. These are in the direction of the effects shown by the experimental measurements. It is also apparent, however, that for $f^2/2\pi \sim \frac{1}{2}$, the contributions of the fourth-order terms are much too small. The $P-P$ total cross section is less than $\frac{1}{10}$ that for the $N-P$ scattering.

The failure of the scalar theory to give a better qualitative

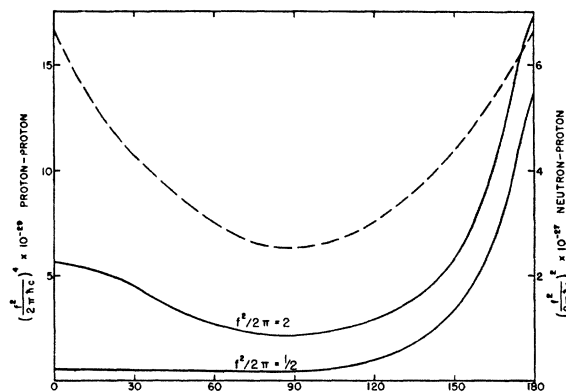


FIG. 1. $N-P$ scattering (solid curves) and $P-P$ scattering (dashed curve) at 180 Mev for the charged scalar theory.