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[12]For these calculations we have used $\sigma_p = 45.10$ mb, $\sigma_n = 43.00$ mb, $\rho_p = -0.12$, $\rho_n = 0.14$, and $a = 0.297$ F^2. These values have been obtained from measurements by Bugg et al. (Ref. 11) and from measurements by L. F. Kirillova et al., Yadern. Fiz. 1, 533 (1965) [translation: Soviet J. Nucl. Phys. 1, 379 (1965)]; L. F. Kirillova et al., Zh. Eksperim. i Teor. Fiz. 50, 76 (1966) [translation: Soviet Phys.-JETP 23, 52 (1966)]; L. Kirillova et al. (unpublished); L. F. Kirillova, private communication.

HIGH-ENERGY PHOTOPRODUCTION OF ρ^0 MESONS FROM HYDROGEN AND DEUTERIUM*

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We have measured the photoproduction of ρ^0 mesons from hydrogen and deuterium as a function of the photon energy, k_γ, and the square of the momentum transfer, t. The assumption that the ρ is produced by a purely diffractive mechanism is midly contradicted by the data.

The photoproduction of ρ^0 mesons on hydrogen and deuterium has been measured at the Cornell University 10-GeV electron synchrotron at average photon energies of 4 to 9 GeV. The apparatus is shown in Fig. 1. The bremsstrahlung beam, which is monitored by a thin ion chamber upstream, passes through a 5-in. liquid target and into a uranium beam stop. Photoproduced ρ's decay into $\pi^+\pi^-$ pairs; the π^+ and π^- go through separate "arms" of the magnet system. A sixfold coincidence in the scintillation counters triggers the optical spark chambers. The entire magnet system is mounted on a platform which rotates vertically (to ~7°) about the target, thus varying the production angle. The spark-chamber pictures are used for high-resolution analysis of the data taken on heavy nuclei,[1] and serve only for qualitative checks on the hydrogen-deuterium data.

We study the dependence on incident photon energy k_γ, and on $m_{\pi\pi}$, the rest mass of the $\pi\pi$ system. Mass spectra are obtained by varying the magnetic fields with their ratio fixed. These spectra are dominated by the ρ resonance. Some details of the shape of this resonance are discussed in the following Letter[1] which describes results from various nuclei. Similar spectra are observed from all nuclei. k_γ is varied by moving the target along the beam and changing the magnetic field.

The data presented in Figs. 2 and 3 all repre-

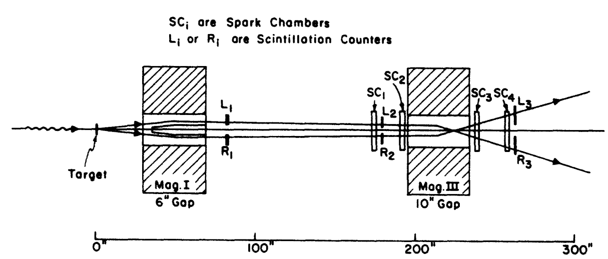

FIG. 1. Top view of apparatus.

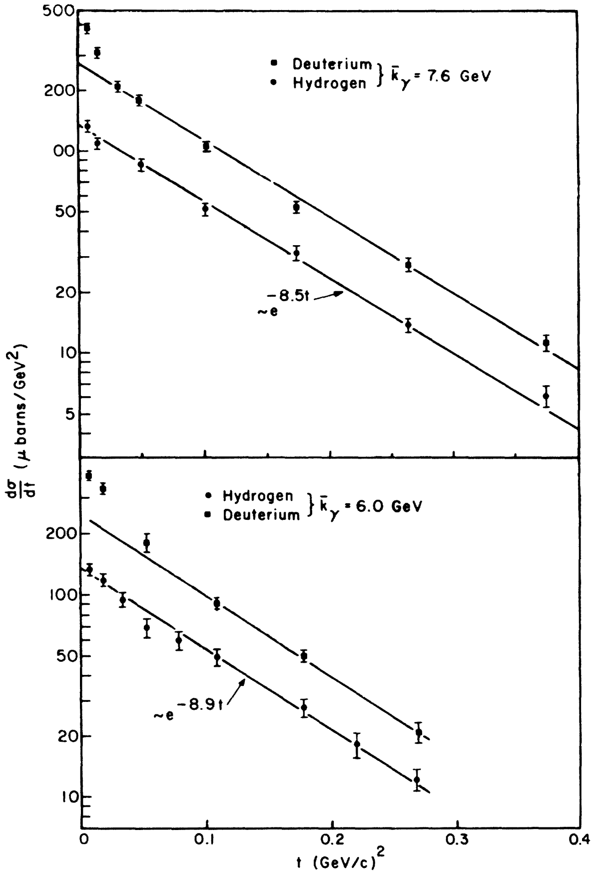

FIG. 2. t dependence of the hydrogen and deuterium cross sections. For large t values, hydrogen and deuterium have the same t dependence. The deuterium shows coherent production as $t \to 0$. The slopes of the curves for $k_\gamma = 7.6$ GeV are 8.5 ± 0.5 $(\mathrm{GeV}/c)^{-2}$ and at $k_\gamma = 6.0$ GeV are 8.9 ± 0.7 $(\mathrm{GeV}/c)^{-2}$.

sent measurements at $m_{\pi\pi} = 770$ MeV, the peak of the ρ^0 mass spectrum. Cross sections are deduced from these measurements assuming a relativistic Breit-Wigner shape with a Jackson-type[2] width and $\Gamma_\rho = 120$ MeV. At large angles, mass spectra were analyzed to ascertain whether "background" subtractions were needed. In each case the mass spectrum for constant t was similar to the spectra at 0° and no subtraction was necessary.

Since we detect only those ρ decays which are approximately transverse to the ρ direction, we must make an assumption about the decay distribution in order to extract ρ cross sections. We assume the ρ-decay angular distribution to be given by $\sin^2\theta$ where θ is the c.m. polar angle relative to the ρ direction of flight. This is consistent with the diffraction model used in this and the following Letter.

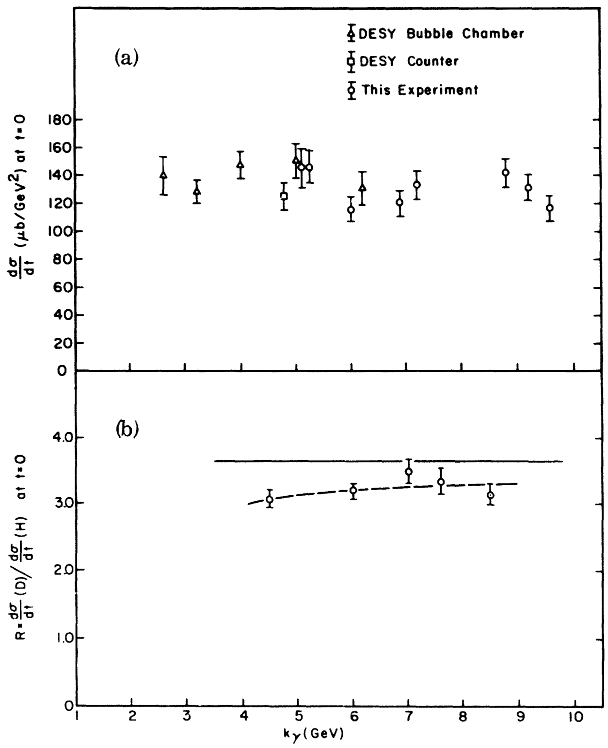

FIG. 3. (a) $d\sigma/dt|_{t=0}$ as a function of k_γ. The cross section is approximately constant and equal to 130 μb/GeV^2 between 4 and 9 GeV. (b) The ratio of the deuterium to hydrogen cross sections at $t=0$. The line drawn at $R=3.64$ is the prediction for pure diffraction production. The average value of the measured ratios is 326 ± 0.10.

We correct the data for various small effects. Typical values are as follows: beam conversion in the target, $+5 \pm 1\%$; beam monitoring, $0 \pm 3\%$; interaction in target and counters, $+5 \pm 1\%$; decay in flight, $+4 \pm 2\%$; empty-target background, $-30 \pm 5\%$ at hydrogen but much smaller for other nuclei and with a t distribution approximately that of carbon; scanning efficiency, $0 \pm 0\%$ (since no important conclusion is based on spark-chamber information); aperture calculation, $0 \pm 3\%$; nonresonant background, $0^{+0}_{-10}\%$ (discussed further in the next paper); and inelastic events, $0^{+0}_{-3}\%$. (For the absence of low-mass recoiling nucleon isobars we must rely on Blechschmidt et al.[3])

Figure 2 shows the t dependence of the data at 7.6 and 6.0 GeV. The deuterium data in each case show a coherent forward peak. At large t (incoherent region) the deuterium t dependence is the same as that of hydrogen. If one characterizes the differential cross section by

$$d\sigma/dt = Ae^{-bt} \tag{1}$$

then, for hydrogen at $k_\gamma = 6.0$ and 7.6 GeV, respectively, $b = 8.9 \pm 0.7$ $(\mathrm{GeV}/c)^{-2}$ and $b = 8.5 \pm 0.5$ $(\mathrm{GeV}/c)^{-2}$. These values are somewhat larger than results obtained at lower energies.[3] Elastic pion-proton and proton-proton scattering show similar behavior at small t values.[4]

Figure 3(a) shows the energy dependence of the hydrogen cross sections at $t=0$, and Fig. 3(b), the deuterium-hydrogen ratio at $t=0$. Previous measurements from hydrogen at lower energies[3] are shown for comparison. The hydrogen cross section appears to be quite constant over the range $k_\gamma = 3$ to 9 GeV, perhaps decreasing slowly with energy.

The measurements on hydrogen and deuterium enable us to determine something about the spin and isospin structure of the production amplitude on nucleons, which we designate by T. The general expression for T is rather complex. However, the most important part of our analysis concerns itself with small angles where the complexity of T is greatly reduced. The $\theta \to 0$ limit of T has the form

$$T = a\vec{\epsilon}_\gamma{}^* \cdot \vec{\epsilon}_\rho + b\vec{\sigma}\cdot\vec{\epsilon}_\gamma{}^* \times \vec{\epsilon}_\rho + c\vec{\sigma}\cdot\vec{u}(\vec{\epsilon}_\gamma{}^* \times \vec{\epsilon}_\rho \cdot \vec{u}), \quad (2)$$

where $\vec{\epsilon}_\gamma$ and $\vec{\epsilon}_\rho$ are the polarization vectors for the photon and ρ, $\vec{\sigma}$ is the nucleon spin, and $\vec{u}$ a unit vector along the incident direction. The t-dependent quantities a, b, and c all have the form $a = a_0 + \tau_3 a_1$, etc., where τ_3 is the nucleon isospin, a_0 and a_1 describe t-channel exchanges with $I=0$ and $I=1$, respectively.

The vector-dominance assumption relates T to a sum of amplitudes for the reactions $VN \to \rho^0 N$, where V is one of ρ^0, ω, or φ; SU(3) implies that, among these, elastic $\rho^0 N$ scatterings dominate. If the latter is diffractive, corresponding to an $I=0$ exchange, we are led to the popular hypothesis that $T = a_0 \vec{\epsilon}_\gamma{}^* \cdot \vec{\epsilon}_\rho \equiv T_0$. We shall show that our data do not agree with this hypothesis. This conclusion does not speak against the vector-dominance model, but only against the assumption that at our energies the only production mechanism exchanges no t-channel quantum numbers.

The differential cross section for production from deuterium, summed over all possible final states of the two-nucleon system, in the closure approximation, is given by

$$d\sigma_D/d\Omega = 4\{|a_0|^2 \tfrac{1}{2}[1+F(t)] + |a_1|^2 \tfrac{1}{2}[1-F(t)] + |D(t)|^2 + |a_0|^2 G(t)\}. \quad (3)$$

Here $F(t)$ is the deuteron's elastic form factor.[5] $D(t)$ is the single-scattering term arising from the spin-dependent portion of T and $|a_0|^2 G(t)$ is the Glauber correction.[6] $D(t)$ is a known function of b, c, and $F(t)$.

In evaluating $G(t)$ we approximate T by T_0. This introduces an insignificant error. Our calculation of $G(t)$ assumes that

$$a_0 = i(em_\rho{}^2/f_\rho)(k_\gamma \sigma_{\rho N}/4\pi)e^{-\frac{1}{2}bt}.$$

$\sigma_{\rho N}$ is the total ρ-nucleon cross section which we take to be 38 mb.[1] We then find $G = -0.089$ at $t=0$ and $G = -0.082$ averaged over 0.2 to 0.5 $(\mathrm{GeV}/c)^2$. Our values of $G(t)$ do not depend on f_ρ or on the photon energy k_γ. They vary approximately linearly with $\sigma_{\rho N}$.

Let R be the deuterium-to-hydrogen cross section ratio at $t=0$. If a_0 were the only nonzero amplitude, we would expect $R = 4(1-0.089) = 3.64$. Figure 3(b) shows a comparison between this value of R and the measured values. The $t=0$ cross sections are obtained using $F(t)$ of Ref. 5 in Eq. (3). t is given by $t = (m_\rho{}^2/2k_\gamma)^2 + k_\gamma{}^2\bar{\theta}^2$ where $\bar{\theta} = 7.5\times 10^{-3}$ rad. The average value of the measured ratios, $R(t=0) = 3.26 \pm 0.10$, differs significantly from the value of 3.64 computed above.[7] This discrepancy could be caused by the nonresonant background, though we doubt it. This difference must be accounted for by one or more amplitudes in which spin or isospin is exchanged in the t channel.

There is no obvious energy dependence for the difference between the calculated and measured ratios. The data exclude neither an energy independent discrepancy nor one that varies as S^{-2}. For example, the dashed curve of Fig. 3(b) shows a discrepancy that varies as S^{-1}. It would be somewhat surprising if the discrepancy were energy independent since it is generally assumed that processes in which quantum numbers are exchanged in the t channel decrease with energy.

We may ask which terms in (2) are responsible for the departure of T from T_0. The available data do not suffice to answer this question. Aside from the hydrogen and deuterium cross sections, there is only one relevant piece of information, the value of the ρ_{00} element of the density matrix of the ρ. At energies of about 4 GeV, ρ_{00} has been measured to be less than 0.05 at $\theta = 0°$.[3] The theoretical expression for this quantity is $\rho_{00}(d\sigma/d\Omega) = |b_0 + b_1|^2$. To proceed further, we must make some assumptions. In order to obtain an indication of the magnitude of the correction terms we shall make the simplifying, though unwarranted, assumption that all the spin-dependent amplitudes are negligible. Thus, we ascribe the entire H-D discrepancy to an isospin dependence of T. With this assumption, it follows from (3) that

$$R^{\text{coherent}} = 4\left(1-\left|\frac{a_1}{a_1+a_0}\right|^2 - \frac{2\,\mathrm{Re}a_0{}^*a_1}{|a_1+a_0|^2}+G(0)\right),$$

$$R^{\text{incoherent}} = 2\left(1-\frac{2\,\mathrm{Re}a_0{}^*a_1}{|a_1+a_0|^2}+2G(t)\right). \quad (4)$$

From the measured values of R, we find

$$\frac{\mathrm{Re}a_0{}^*a_1}{|a_1+a_0|^2} = -0.02\pm0.02,$$

and

$$\left|\frac{a_1}{a_1+a_0}\right| = 0.14\pm0.06. \quad (5)$$

Thus, we require a substantial $I=1$ exchange to account for the discrepancy.

The results of (5) are obtained by averaging all the measurements. We do not mean to imply that these results are independent of energy.

We repeat that, in view of our assumptions, (5) should only be taken as indicative of the nondiffractive amplitudes.[8] It is quite clear that the questions investigated here can only be settled by more data. In particular, information on C of Eq. (2) is required. Such information can be obtained by measuring the density matrix using polarized photons. Thus, a more comprehensive analysis awaits experiments of this kind.

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[1]G. McClellan et al., following Letter [Phys. Rev. Letters 22, 377 (1969)].

[2]The mass distribution we use is given by

$$P_{\mathrm{BW}}(m_{\pi\pi};\Gamma_\rho,m_\rho) = \frac{2}{\pi}\frac{m_{\pi\pi}m_\rho\Gamma(m_{\pi\pi})}{(m_\rho{}^2-m_{\pi\pi}{}^2)^2+m_\rho{}^2\Gamma^2(m_{\pi\pi})},$$

where

$$\Gamma(m_{\pi\pi}) = \frac{m_\rho}{m_{\pi\pi}}\left(\frac{m_{\pi\pi}{}^2/4-m_\pi{}^2}{m_\rho{}^2/4-m_\pi{}^2}\right)^{3/2}\Gamma_\rho;$$

$\Gamma_\rho = 120$ MeV and $m = 770$ MeV. This distribution is normalized to within 1% when cut off at our maximum mass.

[3]H. Blechschmidt et al., Nuovo Cimento 52A, 1348 (1967).

[4]K. J. Foley et al., Phys. Rev. Letters 11, 425 (1963).

[5]For $F(t)$ in Eq. (3) we use the electron-scattering result, which, for small t, can be approximated by $F(t) = (1-56t)$ [t in (GeV/c)^2].

[6]V. Franco and R. Glauber, Phys. Rev. 142, 1195 (1966).

[7]We reported $R = 2.87\pm0.09$ at $\theta = 0°$ to the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 28 August-5 September 1968 (unpublished). This was in error. The correct value is $R = 3.04\pm0.10$. The error was due to the use of an incorrect deuteron form factor. We are grateful to Professor D. R. Yennie for pointing out this error to us.

[8]The relative phase of a_0 and a_1 is determined by the data in the incoherent region where (2) may be inadequate—another reason for viewing the results of (5) with caution.

PHOTOPRODUCTION OF ρ^0 MESONS FROM COMPLEX NUCLEI*

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We have measured the photoproduction of ρ^0 mesons from several complex nuclei. Good agreement with a diffraction model is obtained, and comparison is made with the vector-dominance model. If we write the ρ-photon coupling constant as $em_\rho{}^2/2\gamma_\rho$ we find $\gamma_\rho{}^2/4_\pi = 1.10\pm0.15$.

We report here the results obtained for the production of ρ mesons by 6.2-GeV photons on complex nuclei. The apparatus used is described in the preceding paper,[1] which contains results from protons and deuterons.

Our apparatus determines the directions and momenta of both pions into which the ρ's decay. Assuming the decay angular distribution appro-