[1] J. A. Nolen and J. P. Schiffer, Phys. Letters 29B, 396 (1969); J. P. Schiffer, in Proceedings of the Second Conference on Nuclear Isospin, Asilomar-Pacific Grove, 1969, edited by J. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True (Academic Press, Inc., New York, 1969).

[2] N. Auerbach, J. Hufner, A. K. Kerman, and C. M. Shakin, Phys. Rev. Letters 23, 484 (1969).

[3] A. Bohr, J. Damgaard, and B. R. Mottelson, in Nuclear Structure, edited by A. Hossain, Harun-Ar-Rashid, and M. Islam (North Holland Publishing Co., Amsterdam, The Netherlands, 1967), p. 1.

TOTAL PHOTOABSORPTION CROSS SECTIONS UP TO 18 GeV AND THE NATURE OF PHOTON INTERACTIONS*

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The smallness of nucleon photoabsorption would imply total photonucleus cross sections which vary as the number of nucleons in the nucleus, but if ρ dominance is correct the resulting strong interactions would take place primarily with the surface nucleons. At Stanford Linear Accelerator Center we have measured the photoabsorption in H, D, C, Cu, and Pb and have found cross sections which vary as $\sim A^{0.9}$ indicating that the photon interacts, at least partially, as a strongly interacting particle.

Total cross sections for the photoproduction of hadrons from hydrogen, deuterium, carbon, copper, and lead have been measured at Stanford Linear Accelerator Center (SLAC) at energies up to 18.3 GeV. The high-energy portion of these measurements has been analyzed and yields fundamental information about the nature of the photon interaction with nuclear matter. On the basis of the hydrogen photoabsorption cross section, which implies a photon mean free path of about 800 F, one would expect that the total cross section on a nucleus of nucleon number A should be simply proportional to A; i.e., $\sigma_{\gamma A}=A\sigma_{\gamma p}$. As first pointed out by Stodolsky,[1] however, vector dominance[2] implies that photons interact mainly via the ρ meson, which has a mean free path ~3 F, and consequently the surface nucleons would shadow the rest. If the mean free path were zero, the shadowing would be complete and the cross section would be proportional to the nuclear area. We find cross sections which have an A dependence of about $A^{0.9}$ indicating that the photon interacts in nuclear matter, at least partially, as a strongly interacting particle. The interpretation of this result as a test of ρ dominance depends upon which ρ-production data are used in the comparison.[3-9]

The photoabsorption cross sections were measured by sending photons of known energy into a target and determining whether they were absorbed with the production of hadrons. As shown in Fig. 1, the tagged-photon beam[10] utilized a 1-cm-diam positron beam of energy $E_0 \pm 0.4\%$ which was incident on a thin radiator. Those positrons which radiated a photon of energy E_γ such that $0.74E_0 \leq E_\gamma \leq 0.94E_0$ were deflected by a magnet into one of four counter telescopes which determined the final energy of the positron, E_+. A coincidence count from any tagging telescope indicated that a photon of energy $E_\gamma = E_0 - E_+$, known to $\pm 2.5\%$ of E_0, had entered the target. The tagging system therefore determined the energy of each photon and, with associated anti counters, monitored the photon flux to better than $\frac{1}{2}\%$ accuracy.

The main experimental problem was to separate photon interactions producing hadrons from those yielding electron pairs, which were 100 to 2000 times more numerous, depending on the target. Our solution was primarily geometric, taking advantage of the small opening angles of high-energy pair and Compton-scattering events as compared with the larger angles of hadronic events. Nearly all the background electromagnetic products passed with the beam through holes in the hadron counters $S2a$ and $S2b$ and were vetoed by the lead-scintillator, total-energy shower counter $S1$. Additional discrimination against background was provided by the hadron detectors, which were made of four layers of

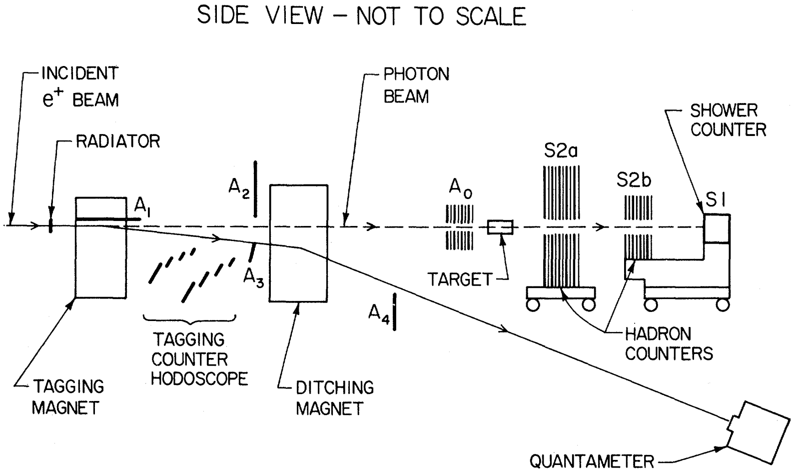

FIG. 1. Schematic representation of the experimental arrangement.

2.5-cm Pb and scintillator. Tests in pion and positron beams showed that requiring either a fourfold coincidence or a very large shower signal gave an efficiency of at least 99% for charged pions of energy 2 GeV or greater, but gave a low efficiency for the electrons of energy less than 500 MeV which would be produced with large opening angles.

With the target removed, about 0.3% of the tagging signals were not accompanied by a large pulse in $S1$; such "false tags" could have resulted, for example, from tridents produced in the radiator. Veto counters A_0, A_1, and A_2 helped keep the false-tag rate this low, which was nevertheless 3 to 60 times the hadronic signal, again depending on the target. The shower veto counter A_0 also kept wide-angle incident photons from being counted in $S2$ or in the monitor signal. 10 in. of lead between A_0 and the target eliminated vetoes from backward pions.

To check that events were not lost outside the detectors, and to adjust the geometrical acceptance with energy so that at least one pion from ρ decays would be intercepted, the $S2a$ and $S2b$ detectors were mounted on separate carts which could be rolled along the beam line. For example, at 13.6 GeV the cross section on deuterium was invariant to better than 2% under changes in the outside or inside acceptances by factors of 2.5 or 3.3 in soldi angle, respectively. This is consistent with our estimate, from known single-pion and low-mass di-pion production, that fewer than 1% of the events would be lost as a result of the non-4π geometry.

Since there are 14 times more pairs per hadronic event in Pb than in H, this A-dependent background was studied carefully. While pair events were strongly peaked forward and hence were generally vetoed by $S1$, it was possible for some rare asymmetric wide-angle pairs to simulate a hadron event if the forward member had insufficient energy to count in $S1$ and the other member had a wide enough angle and sufficient energy to count in $S2b$. In the worst case reported here (8.4 GeV and Pb) these events were studied by moving $S2b$ downstream until the signal from the pairs was nearly equal to the hadronic signal. The pair events then gave characteristic correlated pulse heights (as recorded on magnetic tape) in $S1$ and $S2b$ and could be distinguished from the hadronic events. It was therefore possible to estimate from the pulse-height spectra the fraction of pair events with the normal geometry, and these estimates agreed with analytical wide-angle pair calculations. Corrections of $(5\pm5)\%$, $(3\pm3)\%$, and $(2\pm2)\%$ were made for Pb at 8.4, 13.6, and 16.4 GeV, respectively. The corrections for Cu were less than half as large, and those for other elements were negligible.

Two types of accidental coincidences were important. In the first case, the shower anti counter $S1$ accidentally vetoed good signals about 1% of the time. Anticoincidence counters A_3 and A_4, which reduced the effect of lower energy photons in the unwanted portion of the bremsstrahlung spectrum, helped to keep this rate low. These accidentals were monitored by a delayed circuit and were checked by careful rate-dependence measurements. The second, more serious, type of accidental came from coincidences between false tags and hadron detector signals and was also monitored by delayed circuits. Accurate corrections were made by recording on magnetic tape the complete time spectrum of the coincidences with time-to-amplitude conversion. The spectrum showed a peak, with a width equal to the time jitter of the system, superimposed upon a roughly flat, random background. This accidental background, which was subtracted, varied among the tagging channels and in the weighted average cross section was effectively 3% on D_2 and 14% on Pb.

Corrections of about 5% were made for attentuation of the photon beam in the 0.1-radiation-length targets. Empty-target or target-out subtractions ranged from 4% on deuterium to 35% on lead. The temperature of the liquid targets was monitored with platinum resistors, and the effective target thickness was known to better than 1%.

The corrected total cross sections at average photon energies of 8.4, 13, 6, and 16.4 GeV are given in Table I,[11] and their combined values (divided by $\sigma_{\gamma p}$ in order to reduce the effects of the energy dependence of the nucleon cross section) are plotted in Fig. 2. The errors include statistics, uncertainties in target thickness and pair corrections, and a 15% uncertainty in the accidental corrections. Not included is a ±1% normalization uncertainty due to possible geometric losses, vetoes of good events in $S1$ or A_0, and counter inefficiencies, which is independent of A. It is clear from Fig. 2 that the measured values are well below the line $\sigma_{\gamma A}/\sigma_{\gamma p} = A$; hence the photon does not behave as a particle having only electromagnetic interactions. A significant shadowing is evident, and therefore the general notion from vector dominance, that the photon propagates in nuclear matter as a strongly interacting particle, is borne out.

Quantitative comparison with the predictions of ρ dominance is difficult because the experiments which measure ρ production from complex nuclei are in disagreement. In the limit of high energy, ρ dominance with the assumption of an imaginary forward $\gamma A \to \rho A$ amplitude leads to the relation

$$\frac{\sigma_{\gamma A}}{\sigma_{\gamma p}} = \left[\frac{d\sigma(\gamma A \to \rho A)/dt\,|_{t=0}}{d\sigma(\gamma p \to \rho p)/dt\,|_{t=0}}\right]^{1/2}. \quad (1)$$

This, with the ρ-photoproduction data measured by Cornell[7] and Stanford Linear Accelerator Center–Lawrence Radiation Laboratory (SLAC-LRL)[12] on various nuclei, predicts total cross sections with much more shadowing than we observe. Note that this is a direct comparison of data on nuclei and involves no optical-model calculations. Thus this comparison avoids nuclear-physics calculations and shows unambiguously that our measurements are not compatible with ρ-dominance predictions using the data of Cornell or SLAC-LRL. However, the new data of the Deutsches Elektronen Synchrotron–Massachusetts Institute of Technology (DESY-MIT) group[3,6] would provide closer agreement of our data with vector dominance.

Table I. Cross section in μb for different photon energies.

A \ E_γ (GeV)	7.4-9.4	12.0-15.2	14.4-18.3
1	118.8 ± 2.6	114.0 ± 2.8	113.0 ± 2.5
2	233.6 ± 5.6	218.9 ± 4.0	216.3 ± 4.7
12	1234 ± 25	1153 ± 34	1181 ± 25
64	5252 ± 296	5373 ± 291	5324 ± 268
208	14320 ± 1340	12940 ± 1430	15700 ± 1370

Because of the present uncertainty in the ρ-photoproduction data on complex nuclei, it is useful to compare the A dependence of our total cross-section measurements directly with the predictions of ρ dominance using the optical model to describe the nucleus. The theory with a uniform sphere distribution has been discussed by several authors.[13-15] In addition, Margolis and Tang[16] have performed the calculations with

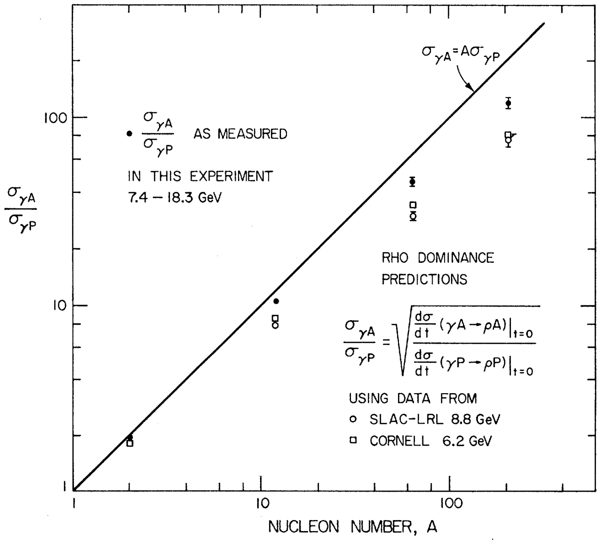

FIG. 2. The ratio of the cross section of nucleus A to that of H as observed (black points) compared with the result expected from a purely electromagnetic photon (line) or from a ρ-dominant photon using Cornell and SLAC-LRL data (open points).

the nuclear density

$$\rho(r) = \frac{\rho_0}{1+\exp[(r-c)/a]}. \tag{2}$$

In these calculations the predicted A dependence is given in terms of the ρ-nucleon total cross section $\sigma_{\rho N}$. The calculations are also dependent upon assumptions made about the nuclear radius, the real part of the amplitude, and nucleon correlations. The A dependence in the form $\sigma_{\gamma A}/A\sigma_{\gamma p}$ is quite insensitive to the ρ-nucleon coupling constant $\gamma_\rho^2/4\pi$, depending upon it only to the extent that its value determines the relative contributions of the ω and φ, which are in any case small. In Fig. 3 the A dependence of our measurements is shown and compared with the optical-model predictions as formulated by Margolis and Tang.[16] We have done the integrals using for c in formula (2) values of 2.35, 4.48, and 6.99 F for C, Cu, and Pb, respectively, deduced from proton-nucleus scattering by Glauber and Matthie,[17] and our average energy 12.8 GeV. Curves are shown for several values of $\sigma_{\rho N}$, with a best fit of 20.4 ± 2.7 mb, assuming no real part of the forward ρ-nucleon amplitude. Even with a 20% negative real part included, the fit is changed by less than the errors given. The curves shown include a contribution varying from 6% on H to 8% on Pb due to the φ, which has less attenuation in nuclear matter than does the ρ or ω (which has attenuation comparable with the ρ). It is clear that the data require a smaller value of $\sigma_{\rho N}$ than is usually obtained.[3] As a test of ρ dominance it is clearer to express this result in terms of the ρ-nucleon coupling constant, which can be done using our hydrogen result for $\sigma_{\gamma p} \approx \sigma_{\gamma N}$ and the relation

$$\sigma_{\gamma N} = \left(\frac{\alpha}{4}\right)\left(\frac{4\pi}{\gamma_\rho^2}\right)\sigma_{\rho N}. \tag{3}$$

The result is $\gamma_\rho^2/4\pi = 0.38 \pm 0.05$, assuming that the ω and φ contribute 18 ± 2 μb to $\sigma_{\gamma N}$. While this result is low compared with the colliding-beam value of 0.52 ± 0.03, where the photon has the ρ mass, it is in good agreement with the value obtained by comparing our hydrogen measurements with ρ production on hydrogen. Using the ρ-dominance relation

$$\sigma_{\gamma p} = \left[4\pi\alpha \frac{4\pi}{\gamma_\rho^2}\frac{d\sigma}{dt}(\gamma p \to \rho p)\bigg|_{t=0}\right]^{1/2}, \tag{4}$$

the data of Anderson et al.[18] at our mean energy 12.8 GeV, and again assuming 18 ± 2 μb contribution from the ω and φ, one finds $\gamma_\rho^2/4\pi = 0.42 \pm 0.04$. This value[19] is in good agreement with our A dependence result and the discrepancy with the colliding-beam result may indicate a mass dependence in the vector-meson amplitudes.

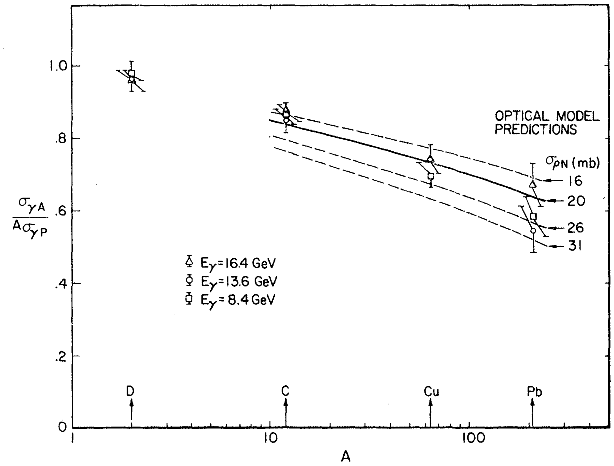

FIG. 3. A comparison of measured values of $\sigma_{\gamma A}/A\sigma_{\gamma p}$ with optical-model calculations. In the calculation Glauber-Matthie radii are used, the real part of the amplitude is assumed to be zero, and the ρ-nucleon cross section is an adjustable parameter.

In conclusion, the A dependence of photon-nucleus cross sections shows that photons interact in nuclear matter much as do strongly interacting particles. Quantitative agreement with ρ dominance is obtained when our measurements are compared with ρ photoproduction on the single proton. Our data are also probably not in serious disagreement with ρ dominance if the DESY-MIT results for ρ production on complex nuclei are used. On the other hand, if the data of Cornell or SLAC-LRL are used, we find violent disagreement with ρ dominance and our cross sections indicate the presence of a contribution which is proportional to A, in addition to a part showing shadowing in the manner of ρ dominance.

We wish to thank Bruce Worster for his help in the construction and execution of this experiment, and also David Fancher for his assistance in the analysis. We have benefited from discussion with a number of theorists, but particular thanks go to Stanley Brodsky and Jon Pumplin who made special efforts to help us. We thank the University of California at Santa Barbara shops, and especially Jim Brandt, for their aid. As visitors at SLAC, the University of California at Santa Barbara group received considerable help from many people, and we wish to express our gratitude for this to W. K. H. Panofsky. Robert Mozley aided us through the loan of apparatus and manpower, and Per Thingstad, Robert Vetterlein, and Domingo Cheng helped considerably in getting our experiment underway. Our special thanks go to Joe Murray who designed and helped test the excellent positron beam, without which the experiment could not have been performed. The accelerator operation was excellent, with the machine achieving a new record of 21 GeV for the highest energy data taking.

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[1] L. Stodolsky, Phys. Rev. Letters 18, 135 (1967).

[2] J. J. Sakurai, Ann. Phys. (N.Y.) 11, 1 (1960); M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[3] Early measurements of ρ production on complex nuclei by the DESY-MIT group gave a coupling constant $\gamma_\rho{}^2/4\pi = 0.45 \pm 0.1$ and a ρ-nucleon cross section $\sigma_{\rho N} = 31.3 \pm 2.3$ mb [J. G. Asbury et al., Phys. Rev. Letters 19, 869 (1967), and J. G. Asbury et al., Phys. Rev. Letters 20, 227 (1968)]. Another interpretation of these data [B. Margolis, Phys. Letters 26B, 524 (1968)] gave $\sigma_{\rho N} = 26 \pm 3$ mb. Recent results by the same group [H. Alvensleben et al., in International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September, 1969 (unpublished)] gave $\gamma_\rho{}^2/4\pi = 0.54 \pm 0.10$ and $\sigma_{\rho N} = 26 \pm 2$ mb, when a 20% negative real part was included for the ρ-nucleon amplitudes. On the other hand, the Cornell [G. McClellan et al., Phys. Rev. Letters 22, 374 (1969), and G. McClellan et al., Phys. Rev. Letters 22, 377 (1969)] and SLAC-LRL [F. Bulos et al., Phys. Rev. Letters 22, 490 (1969)] experiments yield values of $\gamma_\rho{}^2/4\pi = 1.10 \pm 0.15$ and 1.1 ± 0.2 and values of $\sigma_{\rho N} = 39.0 \pm 2.0$ mb and 30^{+6}_{-4} mb, respectively, with no real part of the amplitude. For comparison the value of $\gamma_\rho{}^2/4\pi$ determined from colliding-beam measurements where the photon has the ρ mass is 0.52 ± 0.03 [J. E. Augustin et al., Phys. Letters 28B, 503 (1969)].

[4] Asbury et al., Ref. 3, and Asbury et al., Ref. 3.

[5] Margolis, Ref. 3.

[6] Alvensleben et al., Ref. 3.

[7] McClellan et al., Ref. 3, and McClellan et al., Ref. 3.

[8] Bulos et al., Ref. 3.

[9] Augustin et al., Ref. 3.

[10] D. O. Caldwell, J. P. Dowd, K. Heinloth, and M. D. Rousseau, Rev. Sci. Instr. 36, 283 (1965), provides a detailed description of this type of beam.

[11] Total cross-section measurements on protons and nuclei up to Cu have recently been reported. H. Meyer, B. Naroska, J. H. Weber, M. Wang, V. Heynen, E. Mandelkow, and D. Notz, in International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September, 1969 (unpublished).

[12] Data on C, Cu, and Pb from Bulos et al., Ref. 3. The cross section on hydrogen of 122 ± 12 μb/GeV^2 was reported by the same group at the meeting of the Division of Particles and Fields of The American Physical Society, Boulder, Colorado, 18-22 August 1969 [F. Bulos et al., to be published].

[13] S. J. Brodsky and J. Pumplin, Phys. Rev. 182, 1794 (1969).

[14] M. Nauenberg, Phys. Rev. Letters 22, 556 (1969).

[15] K. Gottfried and D. R. Yennie, Phys. Rev. 182, 1595 (1969).

[16] B. Margolis and C. L. Tang, Nucl. Phys. B10, 329 (1969).

[17] R. J. Glauber and G. Matthie, Istituto Superiore di Sanità, Laboratori di Fisica, Report No. ISS 67116, 1967 (unpublished).

[18] R. Anderson et al., Stanford Linear Accelerator Center Report No. SLAC-PUB-644, 1969 (to be published).

[19] A value of $\gamma_\rho{}^2/4\pi = 0.40 \pm 0.03$ was derived by Z. G. T. Guiragossián and A. Levy, Stanford Linear Accelerator Center Report No. SLAC-PUB-581, 1969 (to be published), in a comparison of pion photoproduction with ρ production by pions.

LIGHT-CONE COMMUTATOR AND HIGH-ENERGY LEPTON-HADRON INELASTIC SCATTERING*

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An extension of the chiral $[SU(3) \otimes SU(3)]_{\gamma_5}$ equal-time commutation relations to the light cone is proposed based on a universality defined by the $[SU(3) \otimes SU(3)]_\beta$ algebra. Consequences concerning asymptotic lepton-hadron inelastic scattering are derived and found to be in good agreement with experiment.

The Fubini–Dashen–Gell-Mann sum rule has been shown[1] to be essentially[2] equivalent to the relation [we consider only forward ($t = 0$) amplitudes[3]]

$$\tfrac{1}{2}\int dx_+ [J^a(x), J^b]\delta(x_-) \doteq i f^{abc} J^c \delta(\vec{x})\delta(x_-), \tag{1}$$

where $J^a(x) = n^\mu J_\mu{}^a(x)$ $[J \equiv J(0)]$ with $J_\mu{}^a$ ($\mu = 0\text{-}4$, $a = 1\text{-}8$) the octet vector currents ($\tfrac{1}{2}\bar{\psi}\gamma_\mu \lambda^\alpha \psi$ in the quark