Interactions of Hadrons with Nuclei at High Energy. II. Photoproduction*

J. S. TREFIL†

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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The Glauber theory is applied to photoproduction reactions where the final state of the nucleus is not measured. It is found that the theory matches existing data on ρ^0 photoproduction very well. It is shown that $\sigma_{\rho N}$, the ρ-nucleon cross section, can be obtained from these data, and is 25 ± 3 mb. It is argued that in photoproduction of nonvector mesons, similar cross sections can be derived, but that more parameters are involved than in the case of vector mesons. It is predicted that nuclear effects will cause a shift of the central mass in resonance production, and that this shift will depend on the angle of production of the resonance.

I. INTRODUCTION

IN a recent paper,[1] hereinafter referred to as I, the problem of the interactions of high-energy particles with nuclei was discussed in the context of the Glauber multiple scattering theory.[2] In particular, it was pointed out that a large number of particle-nucleon total cross sections which are not directly measureable can be measured by creating the particles inside various nuclei, and then extracting the desired cross sections from the nuclear production amplitude. This technique was called nuclear rescattering, since it depends for its success on processes in which the particle scatters from nucleons inside the nucleus after it has been created. It was argued that by use of the multiple scattering theory, any particle-nucleon cross section could be extracted in this way, provided only that the particle can be created on a nucleus, and it was pointed out that insight into the structure of these resonances in terms of quarks could be obtained by a knowledge of the total resonance-nucleon cross section.

The purpose of this paper is to continue the discussion of I to photoproduction processes. While most of the calculations presented in I involved studies of what it might be possible to do in the way of nuclear rescattering experiments, the situation with photoproduction is quite different, since a rather sizable amount of nuclear production data already exists, and more is expected to become available in the near future.[3,4] In addition, the existence of the vector-dominance model raises question of interpretation for photoproduction processes: questions which do not exist for the processes considered in I. Vector dominance tells us that we can think of photon-hadron interactions as proceeding via a diagram like that in Fig. 1, where the photon first "dissociates" into a set of vector mesons, and then these vector mesons interact with the hadron. When applying this idea to nuclear processes, one is naturally confronted with the problem of whether to regard the dissociation as taking place outside of the nucleus,[5] in which case the reactions look just like hadroproduction from an initial beam of vector mesons, or to regard it as taking place before the individual nucleon on which the production process occurs.[6] We shall argue that despite the apparent difference between these models, they are in fact indistinguishable, so that any conclusion which we draw about particle-nucleon cross sections will not depend on assumptions about the nature of the interaction of the photon with nuclear matter.

Another more serious difficulty associated with vector dominance arises when we consider the production of mesons other than the ρ^0, ω^0, or ϕ^0. Then the nuclear photoproduction cross section is found to depend in a rather complicated way on the elementary production processes, so that a simple A-dependence argument will make it difficult to extract particle-nucleon cross sections. It is argued that good data in the incoherent region will be needed to make a convincing determination on quantities like σ_{f^0N}.

Finally, we shall examine the question of nuclear distortion of resonances. There is no *a priori* reason why a resonance produced in a nucleus should exhibit the same mass dependence as one produced on a proton. We shall see that for wide resonances like the ρ^0 meson, one can expect the nuclear effects to shift the central mass of the resonance. More important, we shall see that these effects will depend on the angle at which the resonance is produced, so that resonances produced in the coherent region will be shifted in a different way from those produced in the incoherent region. This is a

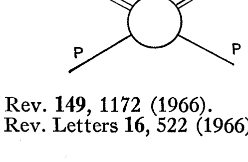

FIG. 1. The vector-dominance mechanism.

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† Present mailing address: Physics Department, University of Illinois, Urbana, Ill.

[1] J. S. Trefil, preceding paper, Phys. Rev. **180**, 1366 (1969).

[2] R. J. Glauber, in *Lectures in Theoretical Physics* (Wiley-Interscience, Inc., New York, 1959), Vol. I; and *Proceedings of the Second International Conference on High Energy Physics and Nuclear Structure* (North-Holland Publishing Co., Amsterdam, 1968).

[3] J. G. Asbury, U. Becker, W. K. Bertram, P. Joos, M. Rhode, A. J. S. Smith, C. L. Jordan, and S. C. C. Ting, Phys. Rev. Letters **19**, 865 (1967).

[4] D. Leith (private communication).

[5] M. Ross and L. Stodolsky, Phys. Rev. **149**, 1172 (1966).

[6] S. D. Drell and J. S. Trefil, Phys. Rev. Letters **16**, 522 (1966); **16**, 532(E) (1966).

prediction which can be checked experimentally, and if it is found to be true, will mean that some care must be taken in comparing resonance shapes from nuclear production processes with those for production on a nucleon. This effect will be important only at comparatively low energies ($E_\gamma \lesssim 10$ GeV).

In Sec. II, we review the formalism which we shall use, discuss its strong and weak points, and discuss the problem of vector dominance outlined above. In Sec. III, we compare theory and experiment for reactions on which data is available, and in Sec. IV we look at the problem of resonance distortion in vector-meson production and discuss the effect of the nucleus on resonance shape. Finally, we turn to the problem of photoproduction of nonvector mesons in Sec. V.

II. DISCUSSION OF FORMALISM

The formalism which we shall use is conceptually quite simple. Consider the reaction

$$\gamma + A \to M + X, \tag{2.1}$$

where M is any meson, A is any nucleus, and X represents the final nuclear state, which we do not observe. One possible way in which this reactions can proceed is illustrated in Fig. 2(a), where the photon travels through the nucleus until it encounters a nucleon, and then the meson M is produced on that nucleon and leaves the nucleus, interacting with other nucleons as it goes. Thus, we can determine σ_{MN}, the M-nucleon total cross section from (2.1). It would appear that there is a difference between a process like this, in which the photon is regarded as having an essentially infinite mean free path in nuclear matter, and one like that in Fig. 2(b), where vector dominance has been used to describe the interaction of the photon with the nucleus as a whole.

We shall argue that this is not, in fact, the case. It has been known for some time[7] that in the case that M is a vector meson (V), these two models are identical. In

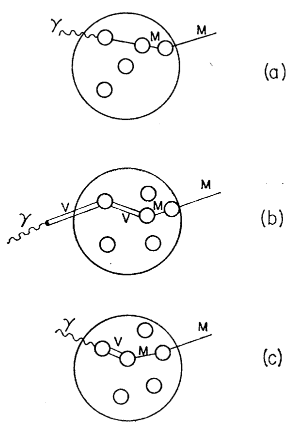

FIG. 2. Some multiple-scattering diagrams.

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

terms of multiple-scattering diagrams, this conclusion is obvious, as we can see by comparing Figs. 2(a) and 2(b). If we replace the $V \to M$ vertex in the former by the vector-dominance diagram in Fig. 1, we see that these two diagrams, each of which corresponds to a triple-scattering contribution, will be identical. Clearly, this conclusion will hold for each order of the scattering, and hence whether one regards the photon as dissociating inside or outside the nucleus is irrelevant to the result of the calculation.

If M is not a vector meson, the situation is a bit different, since it would appear that for each triple-scattering contribution of the type in Fig. 2(a), there are three of the type in Fig. 2(b), corresponding to the $V \to M$ transition taking place on each of the three perturbed nucleons. Thus it would seem that there might be a physical difference which would allow us to make some statements about the manner in which the photon interacts with nuclear matter. It must be remembered, however, that in any multiple-scattering formalism, one must add all of the diagrams which can contribute to a given final state, and, in particular, to Fig. 2(a) we must add the process Fig. 2(c), where a V is photoproduced from the first nucleon, and then converted to an M meson later. This process is of the same order of magnitude as that in Fig. 2(a) (as can be seen by replacing the γ-M vertex by the vector-dominance diagram), and hence must be added to it in calculating the amplitude for the process $\gamma A \to MX$. There are thus three diagrams which contribute to the triple-scattering contribution for either model, and, provided that we assume vector dominance holds for the elementary reaction on a nucleon, these sets of diagrams are identical. Summing the multiple-scattering series in each case must then lead to the same result.

Thus, in any photoproduction reaction, one can either take the point of view that the photon has an infinite mean free path in nuclear matter, and then add up all diagrams which contribute to the final state one is calculating, or one can assume that the photon dissociates outside of the nucleus and interacts with nuclear matter as a vector meson. The results will be identical.

It should be emphasized that, while the above argument depends on vector dominance, there is nothing in the multiple-scattering theory which requires vector dominance. The elementary amplitudes are taken from experiment in this theory. Thus, if experimental evidence against vector dominance were to be found, this could be put into the theory also. In this case, the two ways of treating the interaction of the photon with nuclear matter would differ from each other, and presumably one could look for experimental confirmation of one or the other idea. For the moment, however, we shall assume that vector dominance is valid.

With this difficulty out of the way, we can proceed to calculate photoproduction processes. The general technique is to write the amplitude for the production of the meson M on the ith nucleon as

$$g_i(\delta)=[G(i+\gamma)/4\pi]P_{\text{lab}}\sigma_t e^{-\frac{1}{2}B\delta^2}\hat{O}_i e^{i\Delta_m z_i}, \quad (2.2)$$

where $\hat{O}$ is the operator which is connected with the exchange of quantum numbers (e.g., for charge exchange, it would be τ^+), δ is the transverse momentum transfer, Δ_m is the longitudinal momentum transfer associated with the mass change of the production process, and z_i is the z coordinate of the ith nucleon. The elastic scattering amplitudes are written

$$\begin{Bmatrix} h_j \\ f_j \end{Bmatrix}=[(i+\alpha)/4\pi]P_{\text{lab}}\sigma_t e^{-\frac{1}{2}B\delta^2}, \quad (2.3)$$

where f_j (h_j) refers to the scattering of the V (M) mesons from the jth nucleon, and σ_t is the total V-N (M-N) cross section.

The amplitude for the production from a nucleus can then be written as

$$A=\langle\psi_f|F|\psi_i\rangle, \quad (2.4)$$

where ψ_i (ψ_f) represents the initial (final) nuclear state, and F represents the sum over all diagrams that can contribute to a particular reaction. Thus the cross section to go to a given final state is just

$$d\sigma/dt=(\pi/p^2)\langle\psi_i|F^\dagger|\psi_f\rangle\langle\psi_f|F|\psi_i\rangle \quad (2.5)$$

and, if we neglect the energy differences between nuclear states so that we can apply closure, then we can sum over final states to give

$$(d\sigma/dt)(\gamma A\to MX)=(\pi/p^2)\langle\psi_i|F^\dagger F|\psi_i\rangle. \quad (2.6)$$

In principle, we could now insert the nuclear wave functions and the observed amplitudes into this expression and proceed to calculate. In practice, however, it is found necessary to make approximations to obtain workable results. One can approximate in two ways. First, one can make approximations on the expression $F^\dagger F$ and retain realistic nuclear wave functions,[8] or one can take simple but unrealistic nuclear wave functions and treat the particle scattering amplitudes as exactly as possible.[1] Clearly, the choice of which way to proceed depends on what one wishes to study. If one wishes to study the details of nuclear structure by using hadrons as probes, or to study the effect on hadroproduction processes of different types of nuclear distributions,[9] then clearly the first approach is the appropriate one. On the other hand, if one wishes to study effects which are not sensitive to the details of nuclear structure, then the second approach is indicated. It was argued in I that the details of the nuclear distribution are important only in the so-called transition region, where the momentum transfer is about the same order of magnitude as the Fermi momentum, and that in the coherent regions results depend only on the nuclear radius, and not on the details of the shape. In any case, we shall follow the second alternative given above and write

$$|\psi_i|^2\sim\prod_{j=1}^{A} e^{-r_j^2/R^2}, \quad (2.7)$$

where R is fixed by the rms radius of the nucleus as determined by electron scattering.

The actual summing of the multiple-scattering series and integrations over nuclear coordinates and intermediate momentum transfers was carried out in I. The results are simple and can be expressed in closed form, but they are rather long to write out. The amplitude for a process of the type $\pi A\to MX$ is given in Eq. (2.28) of I. To convert to photoproduction, one can simply replace the incident π by a vector meson, and incorporate the dissociation factor $e^2/4\gamma_V$ into the quantity $G(i+\gamma)$ in Eq. (2.2). In the case of vector-meson production, one can use the simpler result given in Eq. (2.12) of I for elastic particle-nucleus scattering and simply multiply by the dissociation factor. We then have expressions for the photoproduction of any meson on any nucleus, and we can proceed to see how well they agree with the experimental data which are available.

III. PHOTOPRODUCTION OF VECTOR MESONS

In this section we shall present some of the results of calculations with the multiple-scattering theory. Since the reaction

$$\gamma+A\to\rho^0+X \quad (3.1)$$

has been studied experimentally, we shall look at it to check the theory and to try to gain some understanding of where the approximations we have made are valid, and where they break down.

It was found in I that for such coherent production reactions, the nuclear photoproduction cross section is sensitive only to the quantities

$$\sigma_0=[G(i+\gamma)]^2/16\pi \quad (3.2)$$

which is the cross section for producing a meson at zero degrees from an individual nucleon [this quantity essentially determines the normalization of the expression for the differential cross section for reaction (3.1)], and the quantity $\sigma_{\rho N}$. The dependence on all other parameters in Eqs. (2.2) and (2.3) was found to be weak. The only other variable which occurs in the amplitude for nuclear photoproduction is the parameter R in Eq. (2.7), and this is determined by the electromagnetic rms radius of the nucleus. Thus, we have an expression for the photoproduction of a ρ^0 meson from any nucleus which depends only on measured quantities and $\sigma_{\rho N}$, the ρ-nucleon total cross section. In addition, if we look at the quantity

$$H=d\sigma/dt(\gamma A\to\rho^0 X)/\sigma_0 \quad (3.3)$$

as a function of A, the dependence on σ_0 (which is

[8] K. S. Kölbig and B. Margolis, Nucl. Phys. **B6**, 85 (1968); B. Margolis, Phys. Letters **26B**, 524 (1968).

[9] A. S. Goldhaber and C. J. Joachain, Phys. Rev. **171**, 1566 (1968).

somewhat hard to measure exactly) disappears, and we are left with a rather clean determination of the quantity $\sigma_{\rho N}$. We can then plot H for various $\sigma_{\rho N}$ (see Fig. 3) and decide that

$$\sigma_{\rho^0 N}=25\pm3 \text{ mb}. \quad (3.4)$$

This is to be compared with the result

$$\sigma_{\rho^0 N}=31.3\pm2.3 \text{ mb} \quad (3.5)$$

derived in Ref. 3, using the somewhat simplified approach of Ref. 6 and the result

$$\sigma_{\rho^0 N}=26\pm3 \text{ mb} \quad (3.6)$$

which was obtained in Ref. 8, where it will be recalled, the complementary line of attack on Eq. (2.6) was taken to the one which we have chosen. The fact that this result agrees with ours indicates that the two types of approximations are more or less equivalent. The difference between these values and that of Ref. 3 arises because the comparison between theory and experiment in Fig. 3 was made at a momentum transfer of 0.010 GeV/$c<t<$0.012 GeV/c which does not correspond to forward angle production. This means that the use of the zero angle result of Ref. 6 in the analysis of the data is not strictly justified, and probably explains the difference between the values of $\sigma_{\rho^0 N}$ listed above. In any case, the spread of values obtained here should give some idea of the type of accuracy that one can obtain by using nuclear rescattering methods to deduce total cross sections. As a general rule, 10–20% seems to be the best that one can hope for at the present time. Until someone discovers a way to make a beam of ρ^0 mesons, however, this is probably the only way one has of measuring this type of cross section, and even a 20% determination is then significant.

With this result for $\sigma_{\rho^0 N}$, we can return to Eq. (2.6)

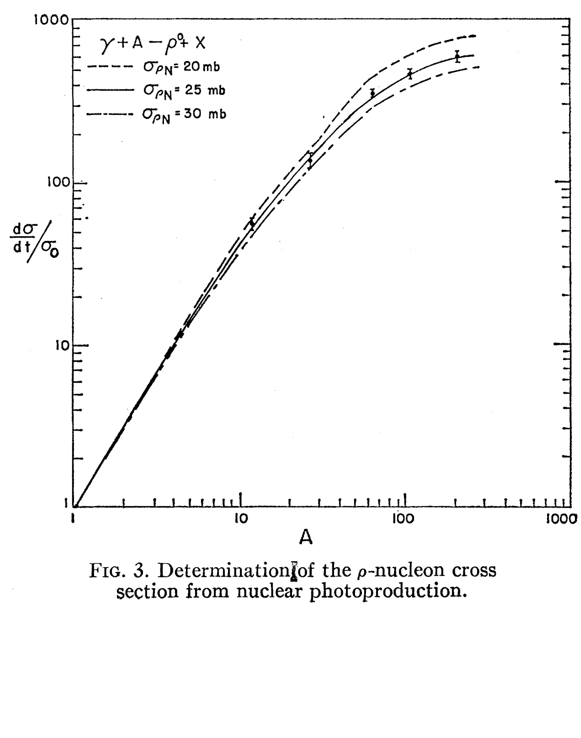

FIG. 3. Determination of the ρ-nucleon cross section from nuclear photoproduction.

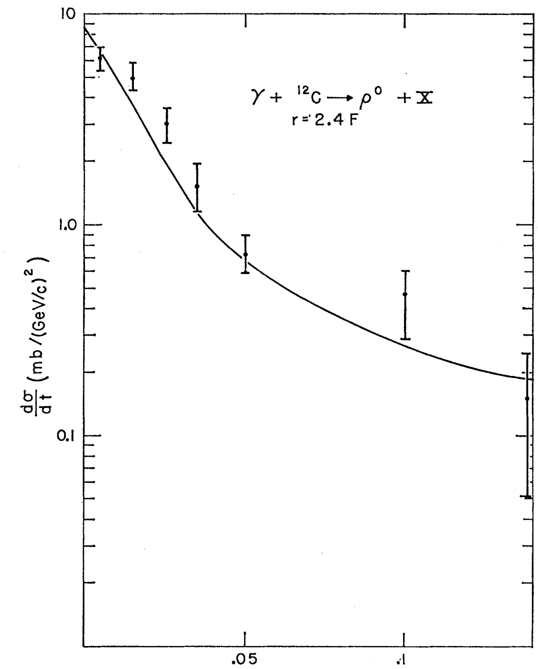

FIG. 4. Comparison of theory and experiment for the reaction $\gamma+{}^{12}\text{C}\rightarrow\rho^0+X$. Data are from Ref. 10 and $\sigma_0=125$ mb/(GeV/c)^2.

and ask how well the multiple-scattering theory matches the observed differential cross sections. This means that we must now work with $d\sigma/dt$ rather than with H, as we did above, and must therefore make some statement about the value of σ_0. In Ref. 10 the value of σ_0 was measured explicitly in the same apparatus in which the nuclear photoproduction was measured. It was found that

$$\sigma_0=125\pm15\ \mu\text{b}/(\text{GeV}/c)^2. \quad (3.7)$$

With this value of σ_0 we can then proceed to calculate the reactions

$$\gamma+{}^{12}\text{C}\rightarrow\rho^0+X \quad (3.8)$$

and

$$\gamma+{}^{27}\text{Al}\rightarrow\rho^0+X. \quad (3.9)$$

The results are shown and compared to the data in Figs. 4 and 5. The agreement is seen to be good both in normalization and in shape of the differential cross section.

When we come to the data of Ref. 3, we do not have a direct measurement of σ_0 available. We therefore fit the curve for one nucleus, and see how the fits for the other nuclei turn out. We find that the best value of σ_0 for the data of Ref. 3 is

$$\sigma_0=166\pm10\ \mu\text{b}/(\text{GeV}/c)^2. \quad (3.10)$$

This is to be compared with the bubble-chamber result

[10] H. Blechschmidt, J. P. Dowd, B. Elsner, K. Heinloth, K. H. Hohne, S. Raither, J. Rathje, D. Schmidt, J. H. Smith, and J. H. Weber, DESY Report No. 67/30 (unpublished).

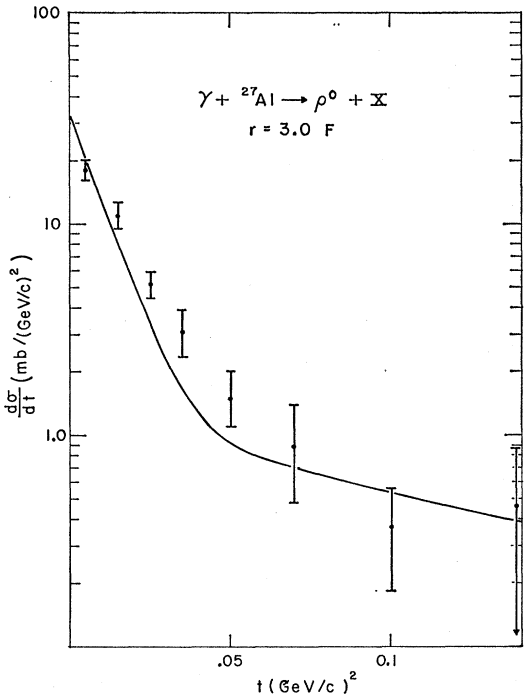

FIG. 5. Comparison of theory and experiment for the reaction $\gamma+{}^{27}Al\rightarrow\rho^0+X$. Data are from Ref. 10 and $\sigma_0=125$ mb/(GeV/c)^2.

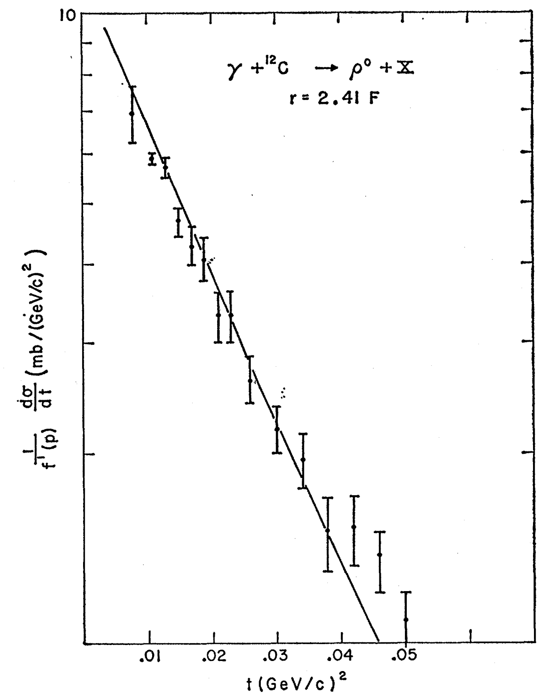

FIG. 6. Data and theory for the reaction $\gamma+{}^{12}C\rightarrow\rho^0+X$, with data from Ref. 3 and $\sigma_0=165$ mb/(GeV/c)^2.

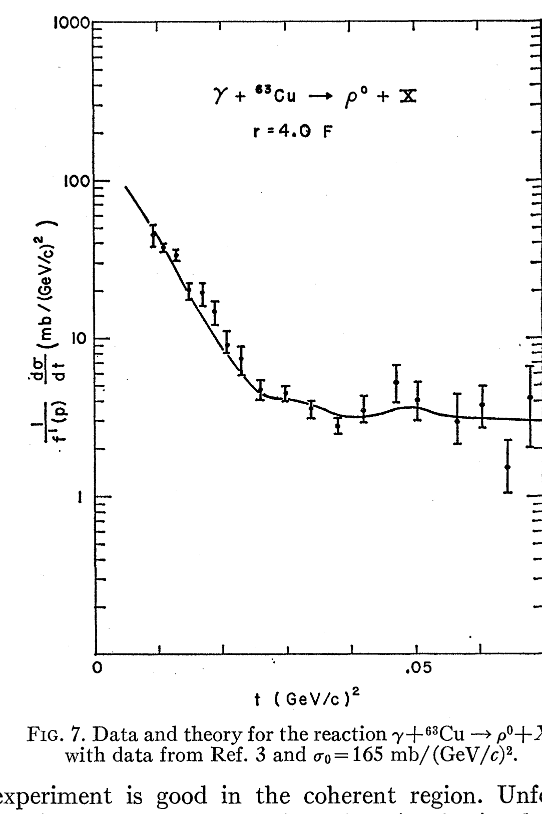

FIG. 7. Data and theory for the reaction $\gamma+{}^{63}Cu\rightarrow\rho^0+X$, with data from Ref. 3 and $\sigma_0=165$ mb/(GeV/c)^2.

of

$$\sigma_0=149\pm15\ \mu b/(GeV/c)^2. \tag{3.11}$$

The fits to the differential cross sections for the reactions

$$\begin{aligned}\gamma+{}^{12}C&\rightarrow\rho^0+X,\\ \gamma+{}^{63}Cu&\rightarrow\rho^0+X,\\ \gamma+{}^{208}Pb&\rightarrow\rho^0+X,\end{aligned} \tag{3.12}$$

are shown in Figs. 6, 7, and 8. As expected, the multiple-scattering model works well inside the diffraction peak, but breaks down in the "transition region" discussed in I, where the results are expected to be sensitive to the details of the nuclear shape, and where our simple Gaussian form in Eq. (2.7) is expected to be inadequate. The problem of the different values of σ_0 needed to fit the two pieces of data is not, I think, of fundamental theoretical significance, especially if one remembers that Refs. 10 and 11 give different values of σ_H, the total production cross section on hydrogen. These differences are of the same order of magnitude as those in σ_0, and indicate that the difficulty is probably experimental in nature. What we can say is that the values of the cross sections in Ref. 10 are consistent within themselves, and that any correction which amounts to an over-all scaling will not affect the agreement of theory and experiment.

With the exception of this minor difficulty, however, we can say that the agreement between theory and experiment is good in the coherent region. Unfortunately, there is not sufficient data in the incoherent region to make a comparison. In the transition region the agreement is not too good, as would be expected,

[11] E. Lohrmann, in *Proceedings of the 1967 International Symposium on Electron and Photon Interactions at High Energies* (Stanford Linear Accelerator Center, Stanford, Calif., 1967).

and this disagreement can be ascribed to the simplified wave function which we have used.

IV. RESONANCE DISTORTION

If we are photoproducting a vector meson of mass m_R, then from Eq. (22) we see that the expression for the nuclear photoproduction will depend on m_R through the minimum momentum transfer $\Delta_m = m_R^2/2P_{\text{lab}}$. If we assume that the meson is produced on the bound nucleon with the same resonance shape as on a free proton, then we can write the inelastic amplitude in Eq. (2.2) as

$$[G(i+\gamma)/4\pi] p e^{\frac{1}{2}C\delta^2 + i\Delta_m z_i} \hat{O}_i P_{\text{H}}(m_R),$$

where $P_{\text{H}}(m_R)$ is the probability of producing a meson of mass m_R on free hydrogen. If we insert this inelastic amplitude into the multiple-scattering series, we can then calculate $P_A(m_R)$, the probability of a meson of mass m_R being produced in the nucleus. It is clear that we can write

$$P_A(m_R) = P_{\text{H}}(m_R) T(m_R, t, \sigma \cdots), \qquad (4.1)$$

where T the transmission function defines the probability that the resonance will be transmitted through the nucleus after it has been produced. Clearly, it will depend on all of the parameters in the problem, including the momentum transfer.

It should be noted that the distortion which we are discussing is a result of the fact that when a resonance is created, there is a certain minimum momentum transfer

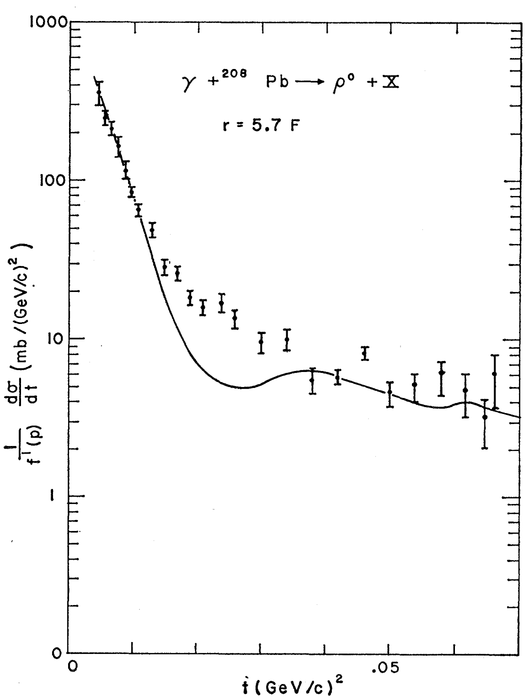

FIG. 8. Data and theory for the reaction $\gamma + {}^{208}\text{Pb} \rightarrow \rho^0 + X$, with data from Ref. 3 and $\sigma_0 = 165$ mb/(GeV/c)^2.

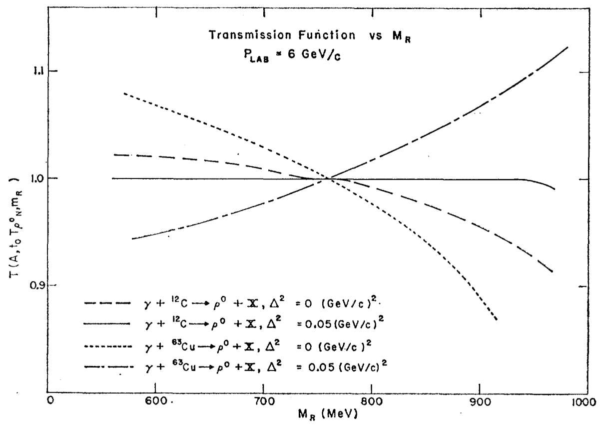

FIG. 9. The transmission function T defined in Eq. (4.1) as a function of resonance mass for various nuclei and various momentum transfers.

associated with the mass change. This momentum transfer is spread over the entire nucleus, so that the nuclear form factor comes into play, favoring lighter mass resonances over heavier ones. We do not consider corrections to resonance shape due to the possibility that the resonance may decay inside of the nucleus. This particular effect has been studied in some detail elsewhere.[12]

At present energies, the minimum momentum transfer in Eq. (2.2) is not negligible when compared to nuclear radii, especially for heavy nuclei. In I, it was found that Δ_m enters the equation as $e^{\frac{1}{4}\Delta_m^2 R^2}$ (for a more general wave function it would be $\rho(\Delta_m^2)$, where ρ is the form factor of the nucleus). Thus, the distortion effect need not be small.

Consider the reaction in Eq. (3.1). Let us assume that on a proton, the ρ^0 shape is given by a Breit-Wigner formula,

$$P_{\text{H}}(m_{\pi\pi}^2) \sim (m_\rho^2 - m_{\pi\pi}^2 + i\Gamma_\rho m_\rho)^{-1}. \qquad (4.2)$$

[It should be clear that the multiple-scattering theory says nothing about what the shape of $P_{\text{H}}(m_R)$ should be. Thus, the Ross-Stodolsky[5] factor of $(1/m_{\pi\pi})^4$ could easily be inserted into the above.]

The transmission function for a series of nuclei and different t values is shown in Fig. 9. A rather striking effect is shown there. While at small t, in the coherent region, the nucleus tends to favor the formation of lighter masses, as would be expected, the situation at higher t is reversed. Here the nucleus seems to favor heavier masses. That these two regions should exhibit different distortions is not surprising, since the physical processes going on are different. In the coherent region, we have a situation where the nucleus is largely unaffected by the interaction, while in the incoherent, we are probably dealing with processes in which there is nucleon ejection.[1] The slight favoring of heavy masses in the incoherent region is thus probably a threshold

[12] K. Gottfried and D. Julius (to be published).

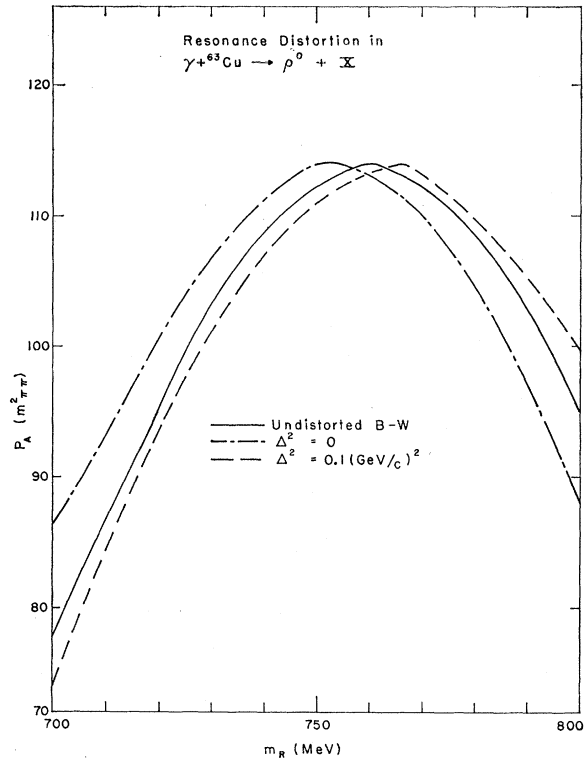

FIG. 10. An example of resonance distortion in ^{63}Cu. The ρ meson is assumed to be produced from a proton in a Breit-Wigner (BW) shape, with $M_\rho=750$ MeV and $\Gamma_\rho=125$ MeV. We show here the nuclear resonance shape for coherent and incoherent production.

effect, due to the fact that heavier masses correspond to momentum transfers which are farther above the Fermi momentum.

In Fig. 10 we show the expected resonance shapes for the photoproduction of ρ^0 mesons on ^{63}Cu. We see that the coherent mass shift is about -10 MeV, while the incoherent mass shift is $+5$ MeV, for a net difference of 15 MeV. The resonance width does not seem to be changed appreciably over the momentum-transfer range considered. Thus we see that in the production of broad resonances on nuclei, the central mass of the observed resonance will depend on the angle at which the resonance is produced. Thus, some care must be taken in comparing resonances which are produced on nuclei and those produced on protons, especially for the heavy nuclei, where the distortion effects are the greatest.

It should also be noted that, since this effect depends on the size of Δ_m, it will disappear as one goes to higher energies, and becomes greater at lower energies.

V. OTHER PHOTOPRODUCTION REACTIONS

When we turn our attention to processes like

$$\gamma+A \to f^0+X \tag{5.1}$$

and

$$\gamma+A \to \begin{Bmatrix} \pi^0 \\ \eta^0 \end{Bmatrix} +X, \tag{5.2}$$

we immediately encounter difficulties when we talk about extracting data by nuclear rescattering techniques. These difficulties, basically, are connected with the fact that we must consider diagrams like that in Fig. 11(a) in which the hadronic interaction is initiated by a ρ mesons, as well as the reaction of Fig. 11(b), where it is initiated by an ω. This means that the amplitude F in Eq. (2.4) must now be written:

$$F=f_\rho F_\rho+f_\omega F_\omega, \tag{5.3}$$

where F_ρ (F_ω) represents the amplitude for the ρ (ω) to produce the final meson on a nucleus, and the constants f_ρ and f_ω are the vector-photon coupling constants, which we shall take to be $f_\rho=\frac{1}{2}\sqrt{3}e^2$ and $f_\omega=e^2/2\sqrt{3}$ in accordance with the usual $SU(3)$ prescription. In what follows, we neglect the ϕ meson because of its extremely weak hadronic interaction. The amplitudes F_ρ and F_ω can now be calculated according to the Glauber theory given in I and reviewed above.

One trivial problem which is encountered is connected with the fact that there are no experimental determinations of $\sigma_{\omega N}$ at present, so that we cannot calculate F_ω entirely from experimental data. This is not a difficulty in principle, however, since one could measure $\sigma_{\omega N}$ by nuclear photoproduction just as we measured $\sigma_{\rho N}$.

A more serious difficulty arises from the fact that σ_0, the elementary production amplitude, no longer factors out of the expression for $d\sigma/dt$, so that the determination of the particle-nucleon cross section will depend on the quantities $G(i+\gamma)$ which appear in F_ρ and F_ω. To see this, write

$$\begin{aligned} F&=G_\rho(i+\gamma_\rho)f_\rho(F_\rho'\hat{O}_L(\rho) \\ &\qquad+[G_\omega(i+\gamma_\omega)f_\omega/G_\rho(i+\gamma_\rho)f_\rho]F_\omega'\hat{O}_L(\omega)) \\ &=G_\rho(i+\gamma_\rho)F_\rho[F_\rho'\hat{O}_i(\rho)+\xi F_\rho'O_L(\omega)], \end{aligned}$$

where $\hat{O}_i$ is the operator defined in Eq. (2.2) and ξ is a complex parameter which is, in general, eneryg-dependent. Thus we see that in this case it will not be possible to look at the quantity $(d\sigma/dt)/\sigma_0$ (as we did when determining the $\sigma_{\rho N}$) to obtain an expression

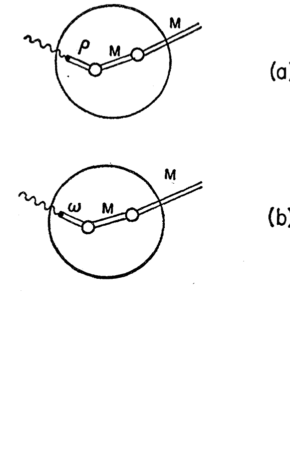

FIG. 11. Contributions to meson photoproduction from the amplitudes F_ρ and F_ω defined in Eq. (5.3).

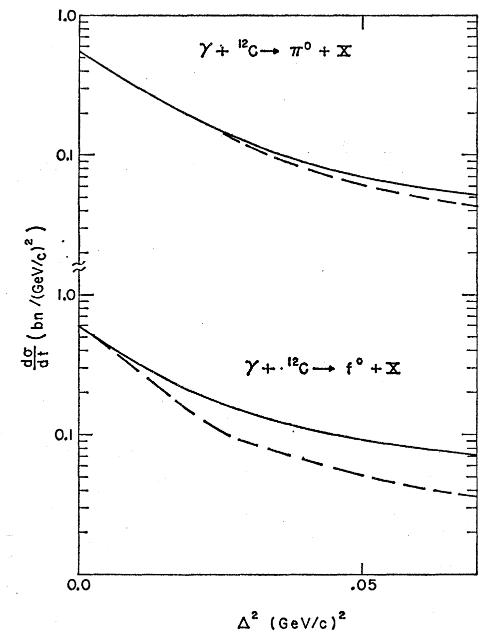

FIG. 12. The coherent production of nonvector mesons at $p_{\rm lab}=6$ GeV/c. We have set $\sigma_{\rho N}=\sigma_{\omega N}=25$ mb, and $\sigma_{f^0N}=\sigma_{\pi N}=30$ mb. The heavy lines show the actual predicted cross section assuming $\xi=1$. The dashed lines show the cross section associated with the piece of the amplitude which contributes to both coherent and incoherent production.

which depends only on the particle-nucleon cross section and know quantities. The problem of determining a cross section like σ_{f^0N} now become one of fitting the differential production cross sections for several nuclei with three parameters (σ_{f^0N}, $[G_\rho(i+\gamma_\rho)]^2$, and ξ) rather than fitting the A dependence of $(d\sigma/dt)/\sigma_0$ with one parameter.

The situation is further complicated by the fact that F_ρ and F_ω may contribute differently to the nuclear production amplitude. For example, in reaction (5.1), the operator $\hat{O}_i(\rho)$ involves a transfer of one unit of isotopic spin to the nucleus, so that on a $T=0$ nucleus F_ρ can contribute only to the incoherent part of the nuclear production amplitude. F_ω on the other hand, can contribute to both coherent and incoherent production. In reaction (5.2), the roles of F_ρ and F_ω are reversed. Thus reactions (5.1) and (5.2) are interesting, not only because data on them should become available soon, but because they represent the two different types of situations one can have in coherent photoproduction processes.

In Fig. 12 we show calculations for these reactions under the assumption that $\sigma_{\rho N}=\sigma_{\omega N}$ and the various production diffraction slopes are 8 $(\text{GeV}/c)^{-2}$. We see immediately that the major effect of the "extra" term (that is, the term which does not contribute coherently) is in changing the effective incoherent nucleon number. Thus the main requirement for seeing the effects of such terms (and thereby determining ξ) is that good data be available in the incoherent region.

We also see that in the production of $T=1$ resonances these extra terms do not play a very large role. This is because they are suppressed by the ratio $f_\omega/f_\rho=\frac{1}{3}$. Thus the effects of the extra parameters will be minimized in such production processes, and the extracted particle-nucleon cross section will be rather insensitive to them.

Finally, we note that in reactions like $\gamma+A\rightarrow K^*+X$ both F_ρ and F_ω appear incoherently, so that under the assumption that $\sigma_{\rho N}=\sigma_{\omega N}$, we find

$$F=[f_\rho G_\rho(i+\gamma_\rho)+F_\omega G_\omega(i+\gamma_\omega)]F_\rho=\tilde{\sigma}_0 F_0$$

so that the expression becomes formally identical with that for $\pi+A\rightarrow K^*+X$ (they differ only in that they have different expressions for σ^0 and $\sigma_{\pi N}$ is replaced by $\sigma_{\rho N}=\sigma_{\omega N}$). Thus the results of I for strangeness exchange reactions can be taken over directly into the photoproduction problem.

We see, then, that except for strangeness exchange, the extraction of particle-nucleon amplitudes in non-vector-meson photoproduction is more difficult than the extraction of the corresponding cross sections in hadroproduction.

VI. CONCLUSION

We have seen how the multiple-scattering theory of Glauber can be applied to photoproduction amplitudes, and have shown that the vector-dominance model of photon-hadron interactions brings no difficulties into the analysis of such reactions. For vector-meson photoproduction, we have seen how particle-nucleon cross sections can be extracted from nuclear photoproduction cross sections. For other coherent photoproduction processes we have seen that, although this type of analysis can be made, it involves a somewhat more complicated approach because of the interference between ρ and ω initiated production events, which are most easily sorted out if good data is collected in the incoherent region.

Finally, there is a rather striking effect which should be observed in the production of resonances if our analysis here is correct, and that is the mass shift in broad resonances between the coherent and incoherent momentum-transfer regions. If this effect is indeed found to exist, then it is clear that the extraction of resonance shapes in nuclear resonance production is somewhat more complicated than had been thought.

Thus we see that the theory of nuclear production processes now stands at the point where the total cross section for almost any particle to scatter on a nucleon can be measured, provided only that the particle in question can be produced on a nucleus.

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