Virtual-Photon Total Cross Sections on Nuclei and the Phases Between Two-Body Amplitudes*

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Experimental results of virtual-photon total cross sections on nuclei are explained in terms of an eikonal model and the corresponding two-body amplitudes $f_{\gamma\rho}$ and $f_{\gamma\gamma}$. The relative phase between these amplitudes has a strong influence on the resultant total cross section and the amount of nuclear shadow observed in the reaction. Given experimental data with fewer uncertainties, this phase could be determined from two-body cross sections and the total cross section on nuclei.

I. INTRODUCTION

Recently there have been measurements[1] of inelastic muon scattering on different nuclei which yield values for the total cross section of virtual photons on nuclei, for values of q^2 between 0.25 and 1.5 GeV^2/c^2. It was noted that no nuclear shadow was found, in contrast to total cross sections of real photons on nuclei.[2] This lack of nuclear shadow is in contradiction to the usual eikonal model for reactions on nuclei and the vector-meson dominance (VMD) model.[3]

We show in this paper that the total cross section of virtual photons on nuclei depends not only on the magnitude of the two-body cross sections involved, but depends strongly on the relative phase ψ between the amplitudes $f(\gamma p\to\gamma p)$ and $f(\gamma p\to\rho^0 p)$ which determine the interference between the one-step and the two-step processes that contribute to the total cross section. This phase could be determined from experimental data on virtual-photon total cross sections on nuclei and measurements of two-body cross sections. At present, however, this is not possible because the experimental uncertainties are too large.

II. THE TOTAL CROSS SECTION ON NUCLEI

The virtual-photon total cross section on nuclei can be calculated with an eikonal model from the two-body reaction amplitudes, in a way similar to the total cross sections of real photons on nuclei. As discussed in the literature,[4] one calculates the elastic forward scattering amplitude $F_{\gamma\gamma}=f(\gamma A\to\gamma A)$ and invokes the optical theorem. $F_{\gamma\gamma}$ is given by Margolis and Tang[4] as

$$F_{\gamma\gamma}=F_{\gamma\gamma}^{(1)}+F_{\gamma\gamma}^{(2)},$$

with

$$F_{\gamma\gamma}^{(1)}=Af_{\gamma\gamma}$$

and

$$F_{\gamma\gamma}^{(2)}=-(2\pi/ik)f_{\gamma\rho}f_{\rho\gamma}\,I(A,q_L,f_{\rho\rho}),$$

where A is the nuclear mass number, and we have ignored the contribution of the vector mesons other than the ρ. The amplitude $F_{\gamma\gamma}$ consists of two parts: The one-step amplitude $F_{\gamma\gamma}^{(1)}$ is produced by elastic scattering of the photon on a nucleon in the nucleus; the two-step amplitude $F_{\gamma\gamma}^{(2)}$ is produced by vector-meson production on one nucleon and photon regeneration on another. $F_{\gamma\gamma}^{(1)}$ is proportional to the elastic scattering amplitude $f_{\gamma\gamma}$ of a virtual photon on a nucleon. $F_{\gamma\gamma}^{(2)}$ is proportional to $(f_{\gamma\rho})^2$, where $f_{\gamma\rho}$ is the ρ^0 photoproduction amplitude by a virtual photon on a nucleon. $I(A,q_L,f_{\rho\rho})$ is a factor which expresses the effects of the longitudinal momentum transfer q_L and the absorption of the intermediate ρ meson within the nucleus. It depends only slightly[5] on the ρ-meson–nucleon elastic scattering amplitude $f_{\rho\rho}$. It is the two-step contribution $F_{\gamma\gamma}^{(2)}$ that is responsible for the nuclear shadow.

Most calculations of the virtual-photon total cross sections on nuclei have been done under the assumption that the amplitudes $f_{\gamma\gamma}$, $f_{\gamma\rho}$, and $f_{\rho\rho}$ have the same phase, or satisfy the constraints of VMD. This assumption leads to good results[6] in the case of total cross sections of real photons, although the use of experimental two-body amplitudes with slight deviations from VMD gives a better fit to the data on nuclei.[7] In the case of virtual photons, the situation is more complicated. Experiments on virtual-photon total cross sections on protons[8] and ρ production in inelastic electron scattering[9] can give information about the magnitude of $f_{\gamma\gamma}$ and $f_{\gamma\rho}$, respectively. However, we point out that it is important to know the relative phase ψ between $f_{\gamma\rho}$ and $f_{\gamma\gamma}$ (i.e., $f_{\gamma\rho}=Ce^{i\psi}f_{\gamma\gamma}$, with C positive). Unfortunately the available experimental data are not very accurate and show discrepancies.[10]

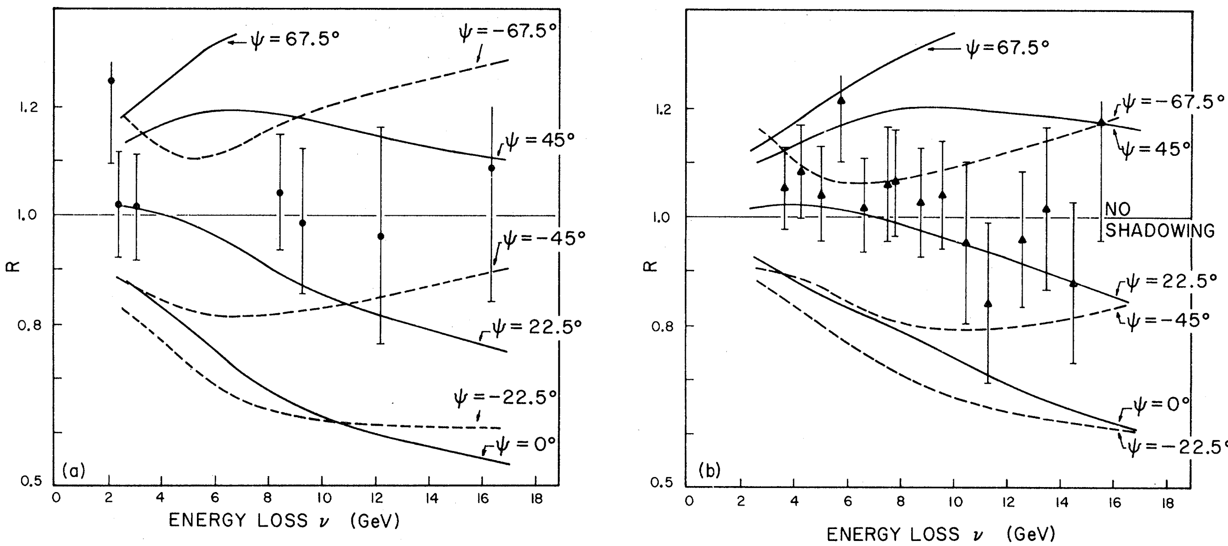

FIG. 1. The ratio R of virtual photon total cross sections on gold ($A = 197$) and on a nucleon, divided by A, is shown as a function of the energy. The value $R = 1$ corresponds to a simple one-step process. The parameters of the calculations are explained in the text. (a) Experiment: $0.25 < q^2 < 0.75$; calculation: $q^2 = 0.5\ \mathrm{GeV}^2/c^2$. (b) Experiment: $0.75 < q^2 < 1.5$; calculation: $q^2 = 1\ \mathrm{GeV}^2/c^2$.

Therefore we have calculated the virtual-photon total cross section using the two-body amplitudes[11] from Ref. 6. The amplitudes include a small real part and satisfy the VMD model. The results of the calculations which are done in the multiple-step production model of Ref. 12 are shown in Fig. 1 (parameter $\psi = 0$). We have also done the calculation for the case where the relative phase ψ between $f_{\gamma\rho}$ and $f_{\gamma\gamma}$ is different from zero. We note that the dependence of the relative cross section on the energy loss is due to longitudinal momentum transfer and slight changes in the two-body amplitudes.

We see from Fig. 1 that the influence of the VMD-breaking phase ψ on the relative cross section is rather strong. If the phase is large enough, one gets coherent enhancement of the cross section, instead of destructive interference between one- and two-step processes in the form of "nuclear shadow."

It has been shown previously[13] that an increased real part of the two-body amplitudes within the VMD model can give rise to effects formally similar to those discussed here, although they are relatively small for realistic values of the real part.

III. CONCLUSIONS

We have shown that the virtual-photon total cross section on nuclei is sensitive to the relative phase ψ between the two-body amplitudes $f_{\gamma\rho}$ and $f_{\gamma\gamma}$. In principle, it is possible to determine ψ from measurements of virtual-photon total cross sections on nuclei and the magnitude of the amplitudes $f_{\gamma\rho}$ and $f_{\gamma\gamma}$. However, with the present experimental uncertainties, it is not possible to decide if the apparent lack of nuclear shadow for virtual photons must be explained by a relative phase ψ of the order of up to +30° or −55°, respectively, or by the fact that the magnitude of $f_{\gamma\rho}$ is smaller than prescribed by the VMD model as indicated by some experiments,[9,7] or by both. We note that eventually, when the experimental data are more accurate, we can use experimental results on the nuclear shadow effect for virtual photons to determine the relative phase ψ between the two-body amplitudes $f_{\gamma\rho}$ and $f_{\gamma\gamma}$.

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[1]H. W. Kendall, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, 1971,* edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N. Y., 1972), p. 254.

[2]D. O. Caldwell *et al.*, Phys. Rev. Letters 23, 1256 (1969).

[3]K. Gottfried, in *Proceedings of the International Symposium on Electron and Photon Interactions at High*

Energies, 1971, edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N. Y., 1972), p. 239.
[4]M. Nauenberg, Phys. Rev. Letters 22, 556 (1969); S. J. Brodsky and J. Pumplin, Phys. Rev. 182, 1794 (1969); B. Margolis and C. L. Tang, Nucl. Phys. B10, 329 (1969).
[5]G. Mennessier and O. Nachtmann, Phys. Letters 34B, 309 (1971).
[6]G. V. Bochmann, B. Margolis, and C. L. Tang, Phys. Rev. Letters 24, 483 (1970).
[7]G. V. Bochmann, Phys. Rev. D 5, 266 (1972).
[8]What is important is the fraction of the hadron electroproduction cross section which goes into the $\rho^0 p$ channel, as described by D. E. Andrews *et al.*, Phys. Rev. Letters 26, 864 (1971).
[9]See D. E. Andrews *et al.*, Ref. 8; C. Driver *et al.*, Nucl. Phys. B38, 1 (1972); E. D. Bloom *et al.*, Phys. Rev. Letters 28, 516 (1972).
[10]H. Harari, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, 1971,* edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N. Y., 1972), p. 303.
[11]The values of the two-body amplitudes and the nuclear parameters are the same as listed in Ref. 6, except that we have here ignored the contribution of the vector mesons ϕ and ω to $f_{\gamma\gamma}$.
[12]G. V. Bochmann, Phys. Rev. D 6, 1938 (1972).
[13]J. Swartz and R. Talman, Phys. Rev. Letters 23, 1078 (1969).

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Compulsory Resonance Formation*

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It is noted that if two mesons are allowed by the quark model to resonate, they do so for $p^* \leq p_0^{MM} \cong 350$ MeV/c, where p^* is the c.m. momentum. The corresponding value for meson-baryon systems is $p_0^{MB} \cong 250$ MeV/c, suggesting (in an optical picture) that the baryon is indeed bigger than the meson. Crucial tests of the rule are provided by exotic baryon-antibaryon systems, for which one expects $p_0^{B\bar{B}} \cong 200$ MeV/c, and by other specific two-body modes which are predicted to resonate not far above threshold.

A dynamical theory of elementary particle resonances does not yet exist. Various models (bootstraps, linear Regge trajectories, harmonic oscillator quark model) have given some partial insights into the spectrum, but attempts to force them to be quantitative have so far met with limited success. Rather, these models are most useful as guides to a correct theory and to further relevant experiments.

In this spirit we should like to point out an approximate regularity in the way two strongly interacting particles form resonances. Tests of this regularity are easily made.

Introduce the following rules[1]:

(a) The observed mesons are made of a quark and an antiquark, and the observed baryons of three quarks.[2]

(b) Two particles may resonate when any antiquark in one can annihilate a quark in the other.

The remarkable fact is that when two particles *may* resonate according to rules (a) and (b), they do so *at least once between threshold and a low momentum p_0 in the center-of-mass system.* For meson-meson systems p_0 is around 350 MeV/c while for meson-baryon systems it is around 250 MeV/c. The case of baryon-antibaryon systems will be discussed presently.

Using the resonance tables of Ref. 3 we have compiled Fig. 1, which shows the center-of-mass momenta p^* for which various meson-meson and meson-baryon pairs form their first resonance above threshold. Each isospin is counted as a separate channel. Both distributions show a remarkable peaking and a rather sharp cutoff above this peak.

As shown by the partial-wave label S, P, D, . . . , in the upper right corner of each box, the first resonance above threshold is generally formed in a rather low relative orbital angular momentum state. The number of S waves and P waves is roughly equal.

The peaking in Figs. 1(a) and 1(b) undoubtedly arises in part from the regular spacing of hadron levels as predicted by various models. On the other hand, it has a simple optical interpretation as well: *Two particles A and B begin forming resonances with one another at a certain well-defined relative distance.* Set

$$p_0^{AB}(R_A + R_B) = \bar{l}\,, \qquad (1)$$