Comment on the point interaction in photon shadowing

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We show that the inclusion of heavy vector mesons in the vector-meson-dominance picture of photon-nucleus interactions cannot explain the observed lack of shadowing. Hence we conclude that the "point interaction" in photon interactions cannot be associated with the existence of heavy vector mesons.

The relative absence of shadowing in photon-nucleus absorption cross sections[1,2] remains a persistent and glaring exception to the rule that photon-hadron interactions can be understood through an application of the vector-meson-dominance model[3] (VMD) or some simple extension thereof. Since the VMD in its simplest form asserts the existence of a connection between vector-meson production from hadrons and elastic photon scattering (and hence, from the optical theorem, total cross sections), the resolution of this problem is of great importance.

One resolution of the dilemma, suggested by a number of authors,[2,4,5] is the postulation of a new type of pointlike interaction for the photon. This new interaction is often connected by the authors with the existence of heavy vector mesons.[2,4] In this note we examine the effect of the one heavy vector meson which has been discovered since this suggestion was made, the ρ',[6,7] and show that a generalized VMD which includes the ρ' and other heavy mesons cannot explain the observed lack of shadowing.

Our conclusion rests on the fact that if the heavy mesons are sufficiently strongly coupled to the photon to have an appreciable effect on shadowing, then the observed total cross section for photon-proton scattering will be less than that calculated by the VMD. This means that if the point interactions do, in fact, exist, they must be a completely new type of photon interaction, and cannot be subsumed into a generalized VMD model which simply adds new vector mesons to those already known.

Let us formulate the problem of shadowing in terms of the standard Glauber multiple-scattering theory.[8] In any process which occurs in a nucleus, there will be A single scattering terms, corresponding to scattering of the projectile on a single nucleon, and higher-order terms. If the incident particle is a photon, we treat the multiple scatterings by assuming that the photon is converted to a vector meson at one nucleon, which must then absorb a longitudinal momentum transfer

$$\Delta_m \approx \frac{m_V^2}{2p_L} \tag{1}$$

(m_V being the mass of the vector meson and p_L the lab momentum of the photon), and then assume that the vector meson reconverts to a photon farther downstream, with the same momentum transfer being absorbed. It is clear that for small p_L the momentum transfer in Eq. (1) will be large, so that the second- and higher-order scatterings will be suppressed by the nuclear form factor. Thus, at small p_L, we expect a total cross section proportional to A.

At higher p_L, the momentum transfer will tend to zero, and the higher-order multiple-scattering terms will become more important. This, in turn, leads to a typically hadronic multiple-scattering series and the usual $A^{2/3}$ type of cross section. The absence of the transition between these two regimes in photonuclear cross sections[1,2] is what we have referred to as a "lack of shadowing." Clearly, the existence of heavier vector mesons which could contribute to the process would raise the value of p_L at which the shadowing should occur, and could therefore be expected to remove the discrepancy.

In order to include all of the vector mesons in the multiple-scattering calculation, we need to know both the meson-photon coupling constant and the meson-nucleon total cross section. The coupling constants, $\gamma_V^2/4\pi$, for the ρ, ω, and ϕ mesons are well known.[1] The couplings for other mesons are not arbitrary, since $\sigma_T(\gamma, \text{nucleon})$ is known to be ~0.118 mb,[2] and can be written using VMD[1] as

$$\sigma_T(\gamma, \text{nucleon}) = \frac{\alpha}{4} \sum_V \frac{4\pi}{\gamma_V^2}\, \sigma_{VN}, \tag{2}$$

where σ_{VN} is total meson-nucleon cross section. Now $\sigma_T(\gamma, \text{nucleon})$ for the sum of ρ, ω, and ϕ is ~0.099 mb. Thus Eq. (2) restricts how strongly we may let the other mesons couple. Assuming that meson-nucleon total cross sections are comparable to those for the ρ, ω, and ϕ, we see that the coupling for the respective mesons must substantially decrease in order to keep $\sigma_T(\gamma, \text{nucleon})$ from growing too large. Whether generalized meson dominance will represent a better description of the photon interaction will depend on the interplay of the form factor vs the coupling of the higher-mass mesons. With this in mind we turn to the multiple-scattering calculations.

We write the forward elastic scattering of the photon as

$$F^{\gamma\gamma}(\vec{\Delta}=0)=F_1^{\gamma\gamma}+F_{\geq 2}^{\gamma\gamma}\,, \tag{3}$$

where $F_1^{\gamma\gamma}$ is the contribution to the amplitude from the single-scattering terms and $F_{\geq 2}^{\gamma\gamma}$ is the contribution from double and higher-order scatterings. For the $F_{\geq 2}^{\gamma\gamma}$, as mentioned previously, we have a two-step process: production, elastic scattering of a meson, and reconversion to a photon. The details of such a process have already been worked out.[9] The major inputs to the process are the elastic meson-nucleon amplitude and the γ-V production amplitude. For the former we write

$$f(\delta)=\frac{p}{4\pi}(i+\alpha)\sigma_{VN}\exp(-\tfrac{1}{2}a\delta^2)\,, \tag{4}$$

where α is the ratio of the real to the imaginary part of the amplitude, σ_{VN} is the total meson-nucleon cross section, and a is the slope of the elastic meson-nucleon amplitude. For the production amplitude on the nth nucleon we have in VMD

$$g_V(\delta)=\frac{(\pi\alpha)^{1/2}}{\gamma_V}f(\delta)\exp(-i\Delta_m z_n)\,. \tag{5}$$

Using these and the general expression of Ref. 9 for proton elastic scattering with a two-step process, we have for $F_{\geq 2}^{\gamma\gamma}$

$$F_{\geq 2}^{\gamma\gamma}=\frac{ip}{16\pi^2\sqrt{\pi}\,(R^2+2a)}\left(\frac{\alpha}{4}\right)\times\sum_V\frac{4\pi}{\gamma_V{}^2}\sigma_{VN}{}^2(1+\alpha^2)\exp[-\tfrac{1}{2}\Delta_m{}^2R^2(1-2/A)]\sum_{k=2}^{A}(-1)^{k+1}\binom{A}{k}\frac{1}{k}\left[\frac{\sigma_{VN}(1-i\alpha)}{2\pi(R^2+2a)}\right]^{k-2}\left[\left(\frac{2}{\pi}\right)^{1/2}\right]^{k-2}\Gamma(\tfrac{1}{2}(k-1))\,, \tag{6}$$

where $R=\frac{2}{3}r_{\text{rms}}{}^2$ and where we have summed over the intermediate meson states. The single-scattering term in the case of VMD is

$$F_1^{\gamma\gamma}=\frac{ip}{4\pi}A\left(\frac{\alpha}{4}\right)\sum_V\frac{4\pi}{\gamma_V{}^2}\sigma_{VN}(1-i\alpha)\,. \tag{7}$$

Finally, $\sigma_T(\gamma, A)$ is given by the optical theorem

$$\sigma_T(\gamma,A)=\frac{4\pi}{p}\,\text{Im}(F^{\gamma\gamma}|_{\Delta=0})\,. \tag{8}$$

The measured parameters of the ρ' are $m_{\rho'}=1.650$ GeV (Ref. 6) and $\gamma_{\rho'}{}^2/4\pi=6\gamma_\rho{}^2/4\pi=3.8$.[10] The experimental values of $\gamma_{\rho'}{}^2/\gamma_\rho{}^2$ range anywhere from 9 to 4, depending on the particular model for the vector-meson breakup; we have taken 6 as a representative value. We also would normally expect that an ω' and a ϕ' would exist as well, although they have not been seen at the present time. We will assume that their coupling should scale in the same way as do the ρ and ρ', so that $\gamma_{\omega'}{}^2/4\pi=6\gamma_\omega{}^2/4\pi$ and $\gamma_{\phi'}{}^2/4\pi=6\gamma_\phi{}^2/4\pi$. We will also assume that $\sigma_{\rho N}=\sigma_{\rho' N}$, $\sigma_{\omega N}=\sigma_{\omega' N}$, and $\sigma_{\phi N}=\sigma_{\phi' N}$. Using the above values for the couplings and cross sections we have from (2), summing over the ρ, ω, ϕ, ρ', ω', and ϕ',

$$\sigma_T(\gamma,\text{nucleon})\approx 0.115\text{ mb}\,.$$

Thus we have almost completely saturated the experimentally observed cross section (~0.118 mb), and we can see that the ρ', ω', and ϕ' have contributed about 16 μb to $\sigma_T(\gamma, \text{nucleon})$. From this it is obvious that the next set of higher-mass mesons (ρ'', ω'', ϕ'') will couple even more weakly as they can contribute only about 3 μb to $\sigma_T(\gamma, \text{nucleon})$.

Using Eqs. (6), (7), and (8) we calculated $\sigma_T(\gamma, A)$ for $A=12$, 64, and 208. The results of the calculations are presented in Fig. 1. We have plotted A_{eff}/A, a measure of the shadowing, as a function of the incident photon energy, where A_{eff}/A is defined by

$$\frac{A_{\text{eff}}}{A}=\frac{\sigma_T(\gamma,A)}{A\sigma_T(\gamma,\text{nucleon})}\,. \tag{9}$$

The experimental points are from Caldwell *et al.*[2] The dashed curves represent the contribution from the ρ meson alone, the dash-dot curves represent the contribution from the ρ, ω, and ϕ, and the solid curves represent the contributions for the ρ, ω, ϕ, ρ', ω', and ϕ'. As can be seen, the additional resonances decrease the amount of shadowing, but not enough in the case of Pb^{208}. At 15 GeV, the experimental point is at ~0.6, while generalized VMD gives ~0.5 for A_{eff}/A.

It is clear from this result that if we were to include higher-mass mesons (referred to generically as the ρ''), we could bring the predictions for nuclear cross sections into agreement with experiments by increasing the coupling constants like $4\pi/\gamma_{\rho''}{}^2$. We find, however, that doing so

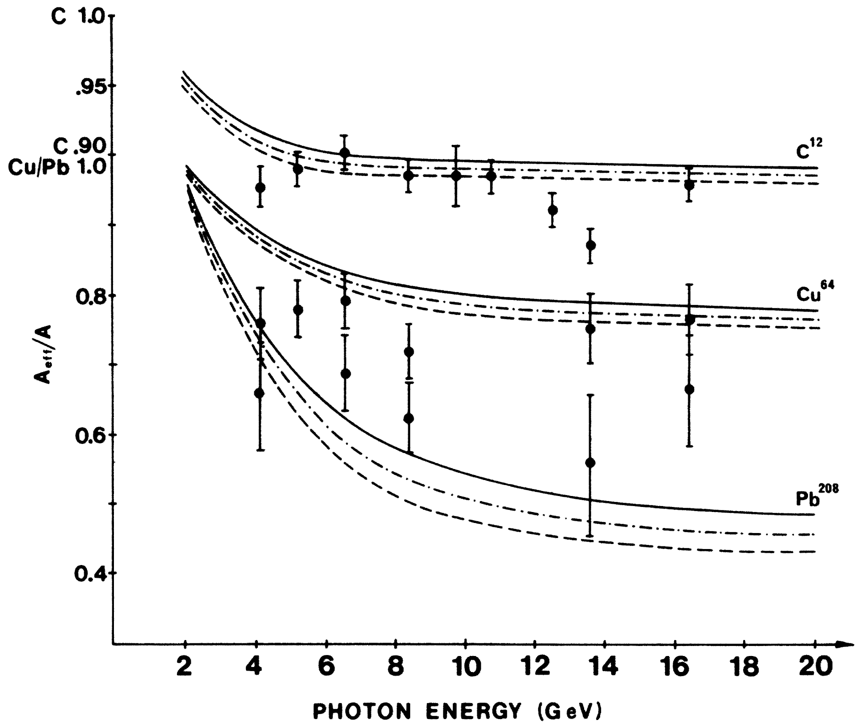

FIG. 1. A_{eff}/A for C^{12}, Cu^{64}, and Pb^{208} as a function of incident photon energy. The dashed curves are the contribution of ρ meson alone; the dash-dot curves are the contribution of the ρ, ω, and ϕ mesons; the solid curves represent contribution from ρ, ω, ϕ, ρ', ω', and ϕ' mesons. The experimental points are from Caldwell *et al.*, Ref. 2.

would increase the cross section on the photon [see Eq. (2)] to 0.131 mb, significantly higher than the experimental number. Thus we see that the two requirements—that the shadowing effects be adequately explained and that $\sigma_T(\gamma, N)$ not exceed its observed value—cannot be accommodated in a simple extension of the VMD model.

It is possible to pick the coupling ratio, $\gamma_{\rho'}^2/\gamma_\rho^2$, within the limits above and adjust $\sigma_{\rho' N}$ so that $\sigma_T(\gamma, N)$ matches its observed value. However, our numerical results show that even with the strongest ρ' coupling ($\gamma_{\rho'}^2/\gamma_\rho^2 = 4$), A_{eff}/A changes only about 1% or 2% from the case $\gamma_{\rho'}^2/\gamma_\rho^2 = 6$. We conclude that whatever the "point interaction" may be in photon interactions, it is probably not associated with the existence of heavy vector mesons, and that the problem of the lack of nuclear shadowing remains a major difficulty for the VMD.

Note added in proof. After completing this work the calculations of Schildknecht[11] were called to our attention. In his work, an attempt is made to explain the lack of shadowing by introducing continuum states in place of the higher-mass mesons which we have used. This procedure introduces a new parameter (which can be thought of as the analog to γ_V) which describes the coupling of the photon to the continuum state. This is regarded as a free parameter and is adjusted to fit $\sigma_T(\gamma, N)$, and the lack of shadowing is then described.

We feel that this procedure, which drops the essential connections between the scattering of the hadronic state and the photoproduction amplitude as in Eq. (2), represents a significant departure from VMD. The new parameter has the effect of increasing the single scattering relative to the higher-order terms, so it plays the same logical role as the point interaction introduced in Ref. 5.

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