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SIZE OF PHOTONS

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A B S T R A C T

We attempt to clarify the question of the effective size of a photon on the basis of a physical picture which has been found useful in understanding the "shadowing" effects in nuclear photoprocesses and the diffractive features in both high energy nucleonic photoprocesses and large $\omega \equiv 2M\nu/Q^2$ nucleonic electroproductions. The result is in contradiction with the result of Cheng and Wu's model calculation, and with the formal estimate of important space-time regions, in the large ω region. Origins of this disagreement are analyzed.

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The question of the effective size of a photon has recently received considerable attention, largely due to the new experiments of γ electroproduction performed at various laboratories ¹⁾. Although the results of these experiments do not yet form a consistent trend, they do suggest the possibility of a changing effective size of a virtual photon as Q^2 or $\omega \equiv 2M\nu/Q^2$ changes. When the accuracy of these experiments is improved, a consistent picture should emerge in the near future.

We attempt in this note to clarify the question of the effective size of a photon on the basis of a physical picture which has been found useful to understand the "shadowing" effects in nuclear photoprocesses ²⁾⁻⁴⁾ and the diffractive features in high energy nucleonic photoprocesses ⁵⁾ and in large ω nucleonic electroproductions ^{5),6)}. The result regarding the effective size of a virtual photon in the large ω region, which follows naturally from this physical picture, is in qualitative disagreement with the result of Cheng and Wu's model calculation ⁷⁾ and with the formal estimate of important space-time regions on the basis of smoothness assumptions ⁸⁾. Possible flaws in these latter considerations are pointed out. The difference can be unambiguously checked by experiment. The outcome has an important bearing, in addition to testing the physical picture we are pursuing, on the usefulness of those programs based on the assumption of light cone dominance, in the large ω region.

The question of a changing effective size exists even in the case of a real photon, for which $Q^2 = 0$. It naturally arises from studying the "shadowing" effects in nuclear photoprocesses. Heuristically, the simplest picture for understanding these effects is as follows ²⁾⁻⁴⁾. A physical photon state $|\gamma\rangle$ of energy ν can be expanded to lowest order in e in terms of a "bare" photon state $|\dot{\gamma}\rangle$ (to the lowest order in e) and the eigenstate $|n\rangle$ of the Hamiltonian, which includes the strong interactions but not the electromagnetic interaction H_{EM} :

$$|\gamma\rangle = |\dot{\gamma}\rangle + \sum_n |n\rangle \frac{\langle n | H_{EM} | \dot{\gamma} \rangle}{E_n - \nu} . \quad (1)$$

The hadron states $|n\rangle$ which can contribute to the sum in Eq. (1) are presumably those states that are produced in e^+e^- annihilation processes. The relative importance of these states in photoreactions depends on, among other things, the "uncertainty" factor $(E_n - \nu)^{-1} \sim \Delta t$, which, for large ν , is

$$\Delta t \simeq 2\nu / M_n^2 , \quad (2)$$

where M_n is the mass of the hadron system $|n\rangle$. For a non-resonant system containing N particles, with masses μ_i , transverse momenta $\vec{p}_{i\perp}$ and fractions of the total momentum x_i , the mass M_n is given by

$$M_n^2 \simeq \sum_{i=1}^N (\mu_i^2 + p_{i\perp}^2) / x_i. \quad (3)$$

In nuclear photoprocesses, the "shadowing" effects are due to the hadron component in Eq. (1). The shift from a "volume" effect at low energies to a "surface" effect at high energies can be interpreted as due to the increasing importance of the hadron component, because of the increasing magnitude of the "uncertainty" factor Δt , and also due to a decreasing interaction strength of the "bare" photon state $|\gamma\rangle$ with the target, as the energy increases.

Accepting this interpretation for the "shadowing" effects observed in nuclear photoprocesses, one naturally attempts to generalize and apply the same idea to nucleonic photo and even electroprocesses. This is what is done in Ref. 5). What are the qualitative differences between the "bare" photon state $|\gamma\rangle$ and the hadron states $|n\rangle$ in Eq. (1) that could show up in processes involving the nucleon as a target? Certainly, diffractive features are characteristic of the interactions between the hadron component and the nucleon target at high energy. There is also the obvious difference in their spatial sizes. While a hadron state carries with it an inherent size reflecting the involvement of the strong interactions, the state $|\gamma\rangle$ is conceivably pointlike, to the lowest order in the electromagnetic interaction.

For nucleonic photoprocesses, we know that diffractive features do start to show up as the energy increases, indicating that the hadron component indeed becomes dominant at high energies. Thus, we speculated that the effective photon size in nucleonic photoprocesses is expected to increase from a pointlike one to that of a typical hadron as the energy $\sqrt{s}$ increases⁵⁾, in close parallel to the shift from a "volume" effect to a "surface" effect in nuclear photoprocesses. Specifically, this change in the effective size should manifest itself in a shrinkage of the forward peak, as the energy increases, in the differential cross-sections for nucleon Compton scattering and the γ photoproduction on nucleon. Experimentally, a typical hadron size is indeed revealed for the photon at high energies. But whether a shrinkage of the forward peak with the energy exists is not yet quite clear. In the case of nucleon Compton scattering, the slope parameters measured at DESY at energies

from 2 to 7 GeV seem to be consistently smaller than those obtained at SLAC at energies from 8 to 16 GeV ⁹⁾. However, it is not clear to us whether this difference is not due to a systematic error. In the case of ρ electroproduction, the results depend on the fitting method used to analyze the data. Take the results of the SLAC-Berkeley-Tufts collaboration ^{10),9)}, using the Söding model ¹¹⁾ for fitting the data. The slope parameter A is $5.4 \pm 0.3 \text{ GeV}^{-2}$ at $\nu = 2.8 \text{ GeV}$, $5.9 \pm 0.3 \text{ GeV}^{-2}$ at $\nu = 4.7 \text{ GeV}$, and $6.6 \pm 0.3 \text{ GeV}^{-2}$ at $\nu = 9.3 \text{ GeV}$. The trend seems to confirm our expectation. It is strongly urged that the possible shrinkage of the forward peaks with energy be seriously studied experimentally ^{*)}. Its importance lies in the fact that it is an intimate part of an over-all physical picture for the photon.

Extending the picture to electroprocesses, there is the additional variable Q^2 . The "uncertainty" factor $(E_n - \nu)^{-1}$ in Eq. (1) becomes, instead of (2)

$$\Delta t \approx 2\nu / (Q^2 + M_\pi^2). \quad (4)$$

A necessary condition for the hadron component $|n\rangle$ in Eq. (1) to play a significant role in electroprocesses is that $2\nu / (Q^2 + M_n^2)$ should be large, presumably larger than the target size ^{13),5)}. Thus, we speculated that diffractive features can show up in electroproduction data only at large ω values ⁵⁾. As we now know, this is indeed the case experimentally. The most direct evidence comes from the comparison of the proton data with the recent deuteron data ¹⁴⁾. It is then natural to expect that the virtual photon also exhibits a changing effective size as $\omega \equiv 2M\nu/Q^2$ increases ^{**)} , just as in the real photon case. Thus, the forward peak of the differential cross-section for ρ electroproduction on a nucleon target is expected to shrink, as ω increases, from what reflects the spatial extension of the target nucleon alone to that of a typical hadron-hadron elastic scattering.

^{*)} It may be worth mentioning that a geometrical interpretation of the dip mechanism expects a shift of the dip position with the sizes of the colliding particles ¹²⁾. Is there a shift of the dip in π^0 photoproduction when the photon energy increases, say, from 2 GeV to 7 GeV?

^{**)} The parameter $\omega' \equiv 2M\nu / (Q^2 + m_\rho^2)$ should be a better parameter than ω , especially when Q^2 is not large. This will be understood in the rest of this paper.

It is clear from the preceding discussion that as long as the hadron component in Eq. (1) dominates, the effective size of the photon is an "average" of those contributing hadron states $|n\rangle$ in the sum. Because of Eq. (2) or Eq. (4), states of low mass M_n are generally favoured, and the effective photon size is, in general, a reflection of the sizes of these states. The mass spectrum observed in e^+e^- annihilation experiments indicates that the resonant vector-meson states may be of particular importance. As Q^2 increases, but with ω correspondingly increased so that the hadron component in Eq. (1) remains dominant, the non-resonant states 2π , 3π , $\bar{K}K$, etc., may become relatively more and more important. For each non-resonant state, kinematical configurations corresponding to smaller effective mass M_n are favoured by the uncertainty relation Eq. (4). Typically, $M_n \lesssim Q$. This means that the relative transverse spatial extension of these particles within the system shrinks with Q ⁷⁾. However, each particle in the non-resonant system still carries with it a size, due to the presence of the strong interactions. We therefore expect that insofar as the hadron component in Eq. (1) is dominant, the effective size of the virtual photon should always be that of a typical hadron. Experimentally, the emergence of the diffractive features in deep inelastic scattering data ¹⁴⁾ at large ω values does indicate the dominance of the hadron component in Eq. (1) at large ω values, even though Q^2 is reasonably large. We thus expect that insofar as ω is sufficiently large to be in the diffractive region, a typical hadron-like size should always be revealed for the virtual photon, independent of Q^2 . This is in qualitative disagreement with the result of Cheng and Wu's model calculation ⁷⁾ and with the formal estimate of important space-time regions ⁸⁾, both of which predict that the effective photon size shrinks to zero as Q^2 increases, even in the region of large ω .

Let us first turn our attention to the Q.E.D. model calculation of Cheng and Wu ⁷⁾, the physical relevance of which has been repeatedly advocated by Bjorken ¹⁵⁾. The diagram considered corresponds to the dissociation of a virtual photon into a lepton-antilepton pair, which, after going through a Coulomb potential, recombines to form a virtual photon again. The calculation was conducted by first taking the $\omega \rightarrow \infty$ limit and then investigating the Q^2 dependence of the differential cross-section. Within the context of Eq. (1), the model of Cheng and Wu amounts to the following two assumptions: (i) the second term in Eq. (1) completely dominates over the "bare" photon state $|0\rangle$ when ω is large; (ii) a representative state for $|n\rangle$ in the second term in Eq. (1) is the lepton-antilepton pair, which, being lepton

and antilepton, do not have their own spatial extensions. It is then clear that the size inferred from Cheng and Wu's calculation is a reflection of the relative spatial separation between the lepton and the antilepton in the system. As Q^2 increases, even though ω is at ω , this relative separation shrinks to zero.

It is our opinion that this model calculation may not be physically relevant. The absence of vector-meson states in this model may or may not matter, although we think that they probably play an important role, especially when Q^2 is not too large ^{*}). Our main objection is the total absence of the strong interactions in this model. It is the strong interactions, presumably, which give rise to the spatial extensions to the hadrons. One might argue that the leptons in Cheng and Wu's calculation could be identified with Feynman's partons ¹⁶⁾, which are point-like. But, recall that Feynman's partons are the "bare" particles defined by the free Hamiltonian, and when a hadron is expressed in terms of the partons there is always a cut-off imposed on the transverse momenta of these partons ; the cut-off procedure is simply an effective way of taking into account the size of a hadron. Indeed, if a transverse momentum cut-off is assumed in a Cheng-Wu type calculation, the result would be qualitatively different from Cheng and Wu's original result ; the size would not shrink to zero when Q^2 increases.

That the effective size of a virtual photon shrinks to zero like $1/Q$ has also been cited as a general result following from a formal estimate of the important interaction regions in space-time ⁸⁾. However, the estimates

$$t-z \lesssim 1/\nu, \quad t+z \lesssim 4\nu/Q^2, \quad (5)$$

and consequently the result

$$x_{\perp}^2 \leq (t-z)(t+z) \lesssim 4/Q^2 \quad (6)$$

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^{*}) When Q^2 is not large, say, below 1 GeV^2 , the vector mesons may be of considerable importance. It is plausible that the ρ meson is particularly important in ρ electroproduction. A properly generalized Söding model ¹¹⁾ should prove useful.

depend crucially on a smoothness assumption about the integrand $\langle \text{nucleon} | J_\mu(x) J_\nu(0) | \text{nucleon} \rangle$. Suri and Yennie⁶⁾ have recently emphasized that this smoothness assumption is unlikely to be justified when ω is large, i.e., in the region where the dominance of the hadron component in Eq. (1) is expected. When $t + z$ is large (because ω is large), propagators associated with vector mesons or other particles will give rise to a rapidly oscillating integrand in $t - z$, and important contributions to the integral will no longer be restricted to the region near the light cone. The calculation of Cheng and Wu probably has been thought of as a specific demonstration of the general result Eq. (6). However, a slight modification of their model, which replaces the lepton-antilepton pair by a proton-antiproton pair with form factors, can also serve as a counter example to the result Eq. (6). Thus, when ω is large, the estimates given in Eq. (5) are in general not valid, and statements regarding $x_\perp$ are model dependent. On the basis of the physical picture we have presented in this note, the size of the photon will not shrink to zero as Q^2 increases as long as we are in the diffractive region. If this point of view, which can be unambiguously checked experimentally, is indeed correct, important interaction regions in space-time simply are not restricted to the vicinity of the light cone, when ω is large. This has important implications. The usefulness of those analyses and programs which are formally based on the assumption of light cone dominance may be questionable, when ω is sufficiently large.

For the sake of clarity, we summarize our expectations regarding the effective size of a virtual photon as is to be reflected in the slope parameter of the γ electroproduction forward peak :

- (i) the slope parameter A , as is customarily defined, will increase from a typical value $A \simeq 4-5 \text{ GeV}^{-2}$ at small ω values to $A \simeq 7-9 \text{ GeV}^{-2}$ at large ω values. The shift will take place roughly in coincidence with the emergence of the diffractive features ;
- (ii) when $A \simeq 7-9 \text{ GeV}^{-2}$ has been reached at sufficiently large ω values, A will not sensitively depend on the value of Q^2 , insofar as ω is maintained at those large values ; in particular, A will not shrink to $4-5 \text{ GeV}^{-2}$ as Q^2 increases when ω is large and in the diffractive region.

In addition to the forward peak of γ electroproduction, the effective size of the photon may also be reflected in the transverse momentum (transverse to the photon direction) distribution of the final hadrons that can

be considered as the fragments of the photon. When ω is large, it is expected that there will be abundant particles moving fast along the photon direction ¹⁷⁾. These particles can be considered as the fragments of the photon. If the effective size of the photon is hadron-like, the transverse momentum distribution of these fragments should be approximately the same as is observed in hadron-hadron collisions ; the average transverse momentum should be roughly around 400 MeV. If, on the other hand, the effective size of the photon is point-like, the transverse momentum distribution in the photon fragmentation region should be markedly different from what is observed in hadron-hadron collisions, and the average transverse momentum of these fragments should be much larger than 400 MeV. We expect the former case to be true.

It seems to us that a systematic experimental study of the questions raised in this note is of considerable importance. A clear-cut experimental answer to these questions can help decide on the usefulness of an intuitively appealing physical picture ^{*)} for the photon. It also has important implications on the usefulness of those formal programs based on the assumption of light cone dominance.

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^{*)} According to this picture, "shadowing" effects should also show up in nuclear electroprocesses when ω becomes sufficiently large. The new data from SLAC ¹⁴⁾ which do not show shadowing expected from some model calculation are a worry. A clarification of the experimental situation is needed.

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A D D E N D U M

Replace the paragraph immediately following Eq. (3) by :

In nuclear photoprocesses, the "shadowing" effects can occur only because of the existence of the hadron component in Eq. (1) *). The shift from a "volume" effect at low energies to a "surface" effect at high energies can take place if : (i) the lifetime of the virtual hadron $\Delta t \sim 2v/M_n^2$ becomes longer than the interaction time, which is characterized by its nuclear mean-free-path, so that the strong absorption effect of the hadron can show up ; and (ii) the interaction strength of the bare photon state $|\gamma^0\rangle$ with the target is weak and/or, more likely, decreases with increasing energy.

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*) We wish to emphasize the heuristic nature of Eq. (1). It is true only in free space. Inside the nuclear matter, for example, the situation is complicated by the interactions of the hadrons with the nuclear matter. We thank Professor J.S. Bell for valuable comments, which prompted the revision of this paragraph.