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When Will Electroproduction and Photoproduction Show Diffractive Features?*

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A simple interpretation is given to the diffraction model for electroproduction and photoproduction, on the basis of which we venture to provide answers to the question: When will electroproduction and photoproduction data show diffractive features? Conjectures are also made regarding the region of validity for Sakurai's results on electroproduction.

I. INTRODUCTION

TWO types of models have been advanced for high-energy inelastic electron scattering in the deep inelastic region.[1] These are the parton model and the diffraction model. In the parton model,[2] one is trying to bypass the strong-interaction dynamics. The scattering is considered in a frame, with respect to which the target proton is moving very fast, and in which the electron can be solely viewed as scattering instantaneously off the quasifree constituents, the so-called partons, of the fast-moving proton. In the diffraction model,[3,4] one tries to make good use of our general understanding of the high-energy phenomenology of purely hadronic scattering amplitudes, such as the diffractive nature of the hadron scatterings at high energy. It is possible that both types of models are correct and are actually complementary to each other. By studying both models one would hope to be able to gain insight into different aspects of the problem.

It is known that while the parton model naturally suggests the scaling law, it is not suited for a discussion of the shape and, in particular, the asymptotics of the structure functions. On the other hand, the diffraction model offers better hope for an understanding of the asymptotics at high values of ν for fixed Q^2. In this paper we make a plausible and simple interpretation of the diffraction picture and try to answer the qualitative question: When will the electroproduction data show diffractive features? The diffraction model has been discussed by Sakurai,[4] on the basis of the vector-meson-dominance assumption, and by Harari[3] on the basis of duality. Our thinking regarding the diffraction model parallels that of Sakurai, although we shall not assume the complete saturation of the hadron spectrum of the electromagnetic current by the known vector mesons alone.

In Sec. II, we first present the diffraction picture for photoproduction and estimate, on the basis of the uncertainty principle, the energy required for the photon to be effectively regarded as a hadron during the collision. The consistency of this picture with recent experiments is indicated. We also speculate on the forward peak of the nucleon Compton scattering. In Sec. III, the diffraction picture is generalized to electroproduction. We shall try to establish the region in the $\nu-Q^2$ plane, in which the electroproduction data are expected to show diffractive features. In Sec. IV, we compare our qualitative conjectures with those of Harari.

II. DIFFRACTIVE MODEL FOR PHOTOPRODUCTION

It is known that a photon, in many qualitative respects, behaves *at high energy* like a hadron. A natural interpretation of this general property can be given in terms of a picture in which *the dominant mechanism at high energy is the following: The photon first converts into a hadron system which then proceeds to interact with the target.* In general, when the photon energy becomes higher and higher, more and more massive hadron states could be effectively excited. However, we shall assume that the spectrum of the hadron states, generated by the electromagnetic current, is dominated by low-mass states, of which the most important ones are the vector mesons. This assumption is necessary in order for the diffractive model of the kind we are considering to be useful.

The conversion of a photon into a hadron is, of course, only a virtual process. The photon can be regarded as a hadron only for a time interval consistent with the uncertainty principle. For the conversion of a photon with energy ν into a hadron state of mass m, the energy difference is

$$\Delta E=(\nu^2+m^2)^{1/2}-\nu\simeq m^2/(2\nu)\,, \qquad (1)$$

for large values of ν: $\nu\gg m$. The lifetime of the virtual hadron state is then given, according to the uncertainty principle, by

$$\Delta t\simeq 2\nu/m^2\,. \qquad (2)$$

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[1] For a review of both the theoretical and experimental aspects of electroproduction on a nucleon, see Frederick J. Gilman, in Proceedings of the 1969 International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, 1969 (unpublished).

[2] R. P. Feynman, Phys. Rev. Letters **23**, 1415 (1969); in *Proceedings of the Stony Brook Conference on Weak Interactions, September, 1969* (Gordon and Breach, New York, 1969); J. D. Bjorken and E. A. Paschos, Phys. Rev. **185**, 1975 (1969).

[3] H. Harari, Phys. Rev. Letters **22**, 1078 (1969); H. D. I. Abarbanel, M. L. Goldberger, and S. B. Treiman, *ibid.* **22**, 500 (1969).

[4] J. J. Sakurai, Phys. Rev. Letters **22**, 981 (1969). See also C. A. Piketty and L. Stodolsky, in Proceedings of Topical Conference on Weak Interactions, CERN, 1969 (unpublished).

Thus, for a fixed m^2, the photon is more and more likely to behave like a hadron at higher and higher energies. It is clear that the usefulness of the diffraction model depends critically on the possibility of dominance of the spectrum of the electromagnetic current by relatively low-mass hadron states. The similarity of the photon and hadron at relatively high energy together with the diffractive features of the recent experimental data concerning the photoproduction on a nucleon, to be discussed below, lends support to the assumption of dominance by low-mass states.

Before going on, let us point out the relationship between the assumption of dominance of the spectrum by low-mass states and the assumption of importance of large longitudinal distances in high-energy photoprocesses. This latter assumption has been the starting point of discussions and analyses by Gribov[5] and Ioffe.[6] The photon converts to a hadron, which can exist for a time interval Δt given by (2) before it converts back into a photon. During this time interval, the fast-moving hadron can traverse a longitudinal distance

$$\Delta z \simeq \Delta t \simeq 2\nu/m^2. \tag{3}$$

If the spectrum of the current is dominated by low-mass states, the longitudinal distance Δz becomes larger and larger at increasingly higher energies. The equivalence of the two assumptions is clear.

For convenience, let us take m to be the effective-mass value of the hadron spectrum of the electromagnetic current. We now ask the qualitative question: At what energy ν can the photon be effectively regarded as a hadron? It certainly depends upon the target. In the case of photoproduction on a nucleon, a natural criterion is that the lifetime of the virtual hadron should be larger than the interaction time, or the distance traversed by the hadron larger than the size of the target nucleon. Thus, when

$$2\nu/m^2 > 2R, \tag{4}$$

the photon may be expected to behave like a hadron,[7] where R is the radius of the target nucleon. Consequently, one can expect to observe diffractive features of the photoproduction data only when (4) is satisfied. To have a rough idea, let us take $m \simeq m_\rho$ and $R \simeq 0.8 \times 10^{-13}$ cm. We obtain the condition

$$\nu > 2.5 \text{ BeV}. \tag{5}$$

Experimentally, the preliminary data[8] of the Santa Barbara and DESY groups do begin to show diffractive features around $\nu \simeq 4$ or 5 BeV: (i) The total photoabsorption cross section $\sigma(\gamma p)$ becomes essentially flat starting at 4 or 5 BeV; (ii) $\sigma(\gamma p) \simeq \sigma(\gamma n)$ within 10% at 4 or 5 BeV. Although we should not take seriously the exact numerical value given in (5), the data certainly support the idea we have presented concerning the interpretation of the diffraction model.

On the basis of the diffraction picture, we have a related conjecture concerning the forward peak of the nucleon Compton scattering. At increasingly higher energies when the photon can be effectively regarded more and more as a hadron, we naturally expect the nucleon Compton scattering to show a forward peak more and more resembling a typical hadron-hadron elastic peak,[9] reflecting the overlapping of the two spatially extended hadron objects. On the other hand, when the energy is still not high enough for the photon to behave like a hadron, only the structure of the target hadron is being probed, and the forward peak of the nucleon Compton scattering is expected to show an angular dependence roughly given by e^{-at} with $a \simeq 4$ or 5 BeV^{-2}, where t is the momentum transfer squared. We therefore expect that *as energy increases, the forward peak of the nucleon Compton scattering will shrink from* e^{-at} *to* e^{-2at} ($a \simeq 4$ or 5 BeV^{-2}). We would not be surprised to see the shrinking begin to take place at about $\nu \simeq 4$ or 5 BeV. This transition closely parallels the transition from the "volume effect" to "surface effect" in the case of photoabsorption by nuclei.[7]

III. DIFFRACTION MODEL FOR ELECTROPRODUCTION

It is natural to generalize the diffractive picture given in the previous section for photoproduction to the case of electroproduction. The new feature in this case is the additional variable Q^2. Let us consider in the rest frame of the target nucleon the conversion of a spacelike photon with (mass)$^2 = -Q^2$ and energy ν into a hadron of mass m. The energy difference is

$$\Delta E = (\nu^2 + Q^2 + m^2)^{1/2} - \nu. \tag{6}$$

Noting that $2M\nu/Q^2 \geq 1$ (M being the mass of the target nucleon), we have for sufficiently large ν

$$\Delta E \simeq (Q^2 + m^2)/(2\nu). \tag{7}$$

The time interval during which the spacelike photon can

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[5] V. N. Gribov, SLAC report (unpublished).

[6] B. L. Ioffe, Phys. Letters **30B**, 123 (1969).

[7] The same reasoning has been used in the case of photoabsorption by nuclei to estimate the transition region in which the transition from "volume effect" to "surface effect" takes place. See, for example, J. S. Bell, CERN Report No. TH. 887, 1968 (unpublished); S. J. Brodsky and J. Pumplin, Phys. Rev. **182**, 1794 (1969). Other related references are L. Stodolsky, Phys. Rev. Letters **18**, 135 (1967); V. N. Gribov (Ref. 5); M. Nauenberg, *ibid.* **22**, 556 (1969); K. Gottfried and D. R. Yennie, Phys. Rev. **182**, 1595 (1969); B. Margolis and C. L. Tang, Nucl. Phys. **B10**, 329 (1969).

[8] Quoted by F. J. Gilman (Ref. 1), and H. Harari, in Proceedings of the 1969 International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, 1969 (unpublished).

[9] As this paper was being prepared, we heard from Professor C. N. Yang that preliminary results of an experiment carried out at SLAC seemed to indicate such an angular dependence at photon energies between 12 and 18 BeV.

be regarded as a hadron is

$$\Delta t \simeq 2\nu/(Q^2+m^2). \tag{8}$$

The condition for the spacelike photon to be effectively regarded as a hadron during the collision, by analogy to (4), is

$$2\nu/(Q^2+m^2) > 2R. \tag{9}$$

Compared with the corresponding condition (4) for the real-photon case, this condition tells us that when the photon is off the mass shell in the spacelike region the energy must be higher to counterbalance the off-mass-shell effect in order for the photon to be effectively regarded as a hadron during the collision. On the basis of (9) we therefore conjecture that *as Q^2 increases, the total cross section for virtual-photon absorption will begin to show diffractive characters at higher and higher energies*. If we accept the photoabsorption data as a hint, we expect that the data actually begin to show diffractive features at about

$$\nu \gtrsim R(Q^2+m_\rho{}^2) \simeq 3+5Q^2, \tag{10}$$

where ν and Q are in units of BeV. At large ν and fixed Q^2, there is the relationship

$$\nu W_2 = (Q^2/4\pi^2\alpha)(\sigma_T+\sigma_S). \tag{11}$$

We therefore expect that *at fixed Q^2 the νW_2 function will become essentially flat as a function of ν, and νW_2 (proton) $\simeq \nu W_2$ (neutron) when $\nu \gtrsim 3+5Q^2$*. In the $\nu-Q^2$ plane, the diffraction region is to the right of the line $\nu=3+5Q^2$ (Fig. 1).

We might point out that Gribov[5] has carried out a very careful analysis of the inelastic electron-nucleus scattering from the point of view that large longitudinal distances are important at high energies, an assumption which we have seen to be equivalent to the assumption of dominance of low-mass states. His analysis can be carried over in its entirety to the case of inelastic electron-nucleon scattering. The only difference concerns the condition of the type (9), under which the diffraction model is applicable. Gribov's results essentially agree with Sakurai's,[4] if ρ dominance is imposed on Gribov's expressions. Their extrapolation procedure in Q^2 seems to be very natural. The rationale behind it is that insofar as the condition $\nu/(Q^2+m^2) > R$ is met, the photon-nucleon collision can be effectively regarded as scattering of a *real* hadron off the target nucleon. The physical picture underlying their extrapolation procedure seems quite clear. This understanding also suggests the region of validity in which the qualitative features of Sakurai's results can be hoped to be correct.[10] The region of validity lies to the right of the line $\nu=R(Q^2+m^2)$. It has been pointed out[11] that Sakurai's prediction about the ratio σ_S/σ_T contradicts the preliminary result of the SLAC data. However, the data points which were analyzed do not lie in the region where Sakurai's model is supposed to be valid. The confrontation of the model with experiment is yet to come. It is of great interest to see if the qualitative features of Sakurai's results can meet the challenge of experiment in the diffraction region, i.e., the region to the right of the line $\nu \simeq 3+5Q^2$ in the $\nu-Q^2$ plane.

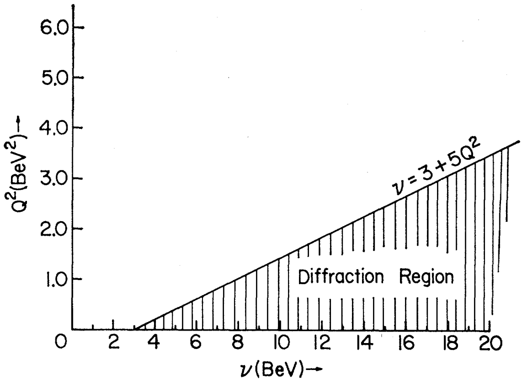

FIG. 1. Diffraction region for electroproduction.

We should also like to point out that the expression for νW_2 given by Sakurai obeys the scaling law in the Bjorken limit in agreement with the parton model. Also, $\nu W_2 \to$ const for large $\omega = 2M\nu/Q^2$. This constancy of νW_2 has been invoked by Ioffe[6] to conclude that large longitudinal distances are important at high energies in electroproduction. This shows the inner consistency of the model.

IV. COMPARISON WITH HARARI'S CONJECTURE

On the basis of duality, Harari[3] conjectured that as Q^2 increases, one should observe a flat ν dependence of νW_2 at lower and lower energies. On the contrary, we expect that as Q^2 increases νW_2 can show diffractive features only at increasingly higher energies. Experimental data to be analyzed in the near future should be able to tell which conjecture is a more relevant one. In this respect, we wish to point out that if Harari's conjecture is correct, then νW_2 should begin to show diffractive features at $\nu < 4$ BeV. This is because photoabsorption data (corresponding to $Q^2=0$) already begin to show diffractive features at $\nu \simeq 4$ BeV. This may prove to be too stringent a restriction for the future data to agree with Harari's conjecture.

V. CONCLUSIONS

We have given a simple interpretation to the diffraction model for photoprocesses. Several qualitative conjectures are advanced, which should be experimentally testable in the near future. Our conjectures are the following:

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[10] We thank Professor J. M. Wang for pointing out the existence of a report by Cho and Sakurai, in which the same point was independently made. It has just appeared as C. F. Cho and J. J. Sakurai, Phys. Letters **31B**, 22 (1970).

[11] R. E. Taylor, in Proceedings of the 1969 International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, 1969 (unpublished).

(i) The forward peak of the nucleon Compton scattering is expected to show shrinking, from an initial dependence e^{-at} shrinking to e^{-2at} eventually (with $a\simeq 4-5$ BeV^{-2}), as the energy increases. The shrinking may begin to take place at $\nu\simeq 4$ or 5 BeV.

(ii) For electroproduction, we conjecture that as Q^2 increases, the νW_2 function can begin to show diffractive features only at increasingly higher energies. The boundary of the "diffraction plateau" (for νW_2) is of the form $\nu=R(Q^2+m^2)$. We venture to guess that it is actually $\nu\simeq 3+5Q^2$.

(iii) The qualitative features of Sakurai's results are more likely to be correct in the diffractive region, i.e., to the right of the line $\nu\simeq 3+5Q^2$ in the $\nu-Q^2$ plane. This is the region where the diffraction model is more likely to be of relevance.

The physical picture we have pursued is a very simple one. But if it can provide a qualitative understanding of the data, its simplicity is its virtue.

Note added in proof. The connection between the energy uncertainty [Eq. (1)] and the longitudinal distance [Eq. (3)] has also been discussed by K. Gottfried, Cornell University report, 1969 (unpublished).

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Unitary Model of Regge Cuts*

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We propose a method for generating Regge cuts based on the multiperipheral model in the approximation of vanishing coupling of the Pomeranchuk trajectory to production processes. We utilize a formalism which explicitly satisfies the full unitarity equations, including inelastic terms, for all connected multiparticle production amplitudes as well as for the two-body amplitude. The sign of the Regge cut coincides with the sign of the cut in the absorptive model, and is opposite to that of the Amati-Fubini-Stanghellini cut. The results are applied to the recent Serpukhov *pp* data.

SINCE the work of Amati, Fubini, and Stanghellini (AFS)[1] appeared in 1962, it has been accepted that Regge behavior and the bilinear character of unitarity implies the existence of Regge cuts. Among the models that evaluate the cut contribution to the two-body scattering amplitude M_{22}, we should mention the absorptive corrections to Regge exchanges,[2,3] the hybrid model,[4] and the eikonal model[5] in which the Regge pole is identified with the first term in the eikonal expansion.

An early attempt to derive an expression for the cut using a detailed model of particle production and elastic unitarity was made by Amati, Cini, and Stanghellini.[6] They used, however, a nonunitary expression for the production amplitude M_{n2}, and unitary corrections to it may strongly modify the cut in M_{22}. For example, Caneschi[7] has shown that an absorptive correction to M_{n2} is sufficient to change the sign of the AFS cut.

With this in mind, we construct a formalism in which unitarity is taken into account for M_{22}, M_{n2}, and M_{nm} $(n, m > 2)$. To do this, we use a generalization of

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[1] D. Amati, S. Fubini, and A. Stanghellini, Nuovo Cimento **26**, 896 (1962).

[2] (a) G. Cohen-Tannoudji, A. Morel, and N. Navelet, Nuovo Cimento **48A**, 1075 (1967); (b) G. Cohen-Tannoudji, A. Morel, and P. Salin, CERN Report No. TH 1003 (unpublished).

[3] See F. Henyey, G. L. Kane, J. Pumplin, and M. Ross [Phys. Rev. **182**, 1579 (1969)] for a justification and applications of the absorptive-model corrections to Regge-pole exchanges.

[4] C. B. Chiu and J. Finkelstein, Nuovo Cimento **57A**, 649 (1968).

[5] R. Arnold, Phys. Rev. **153**, 1523 (1967); S. Frautschi and B. Margolis, Nuovo Cimento **56A**, 1155 (1968); K. A. Ter-Martirosyan, Institute of Theoretical and Experimental Physics, Moscow, Report No. 681, 1969 (unpublished).

[6] D. Amati, M. Cini, and A. Stanghellini, Nuovo Cimento **30**, 193 (1963).

[7] L. Caneschi, Phys. Rev. Letters **23**, 254 (1969).