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VECTOR DOMINANCE, REGGE POLES, AND π^0 PHOTOPRODUCTION*

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(Received 5 August 1968)

The presently accepted Regge parametrization of π^0 photoproduction claims that the $t\sim -0.5$ BeV^2 cross section is completely provided by B exchange. We show that this statement disagrees with vector dominance by a factor of at least 4 and probably 10 or more. Additional $I=0$ poles or cuts are needed both in this process and in the $I=0$ t-channel combination of $\pi+N\rightarrow\rho+N$ cross sections.

The vector-meson-dominance hypothesis relates pion photoproduction processes to the production of transversely polarized vector mesons in pion-initiated reactions.[1] Recent applications[1] of this idea to π^+, π^-, and π^0 photoproduction indicate that such relations are at least consistent with experiment and in some cases one can even detect significant agreement.

Regge-pole theory can be applied to $\gamma+N\rightarrow\pi+N$ as well as to $\pi+N\rightarrow V+N$ reactions. Many experimental features of these processes require the introduction[2] of significant contributions of "exotic" poles and cuts such as the π', B, and ω' poles, the π-P cut, etc.

The purpose of this note is to suggest that once we accept the vector-dominance hypothesis as a valid principle, we may use it in order to test specific Regge "explanations" of the data. In particular, we point out that the currently accepted parametrization[3] of $\gamma+p\rightarrow\pi^0+p$ in terms of ω and B exchange is in violent disagreement with vector dominance and that an extra $ICG=0^{--}$ exchange term, such as an ω' pole or an ω-P cut, is necessary in order to "explain" this process within the framework of Regge theory. We further show that between these two possibilities the ω-P cut is favored.

The usual Regge description of high-energy π^0 photoproduction runs as follows[3]:

(1) Only $C=-1$ neutral mesons can be exchanged in the t channel. The only established ones are ω, ρ, φ, and B.

(2) The $\varphi\pi\gamma$ coupling is vanishing or extremely small[4]; the $\rho\pi\gamma$ coupling is smaller than the $\omega\pi\gamma$ one; the B trajectory is lower than the ω. Hence, ω exchange should dominate.

(3) A pure Reggeized ω exchange predicts a forward dip in $d\sigma/dt$ (in agreement with experiment) and a zero in $d\sigma/dt$ at the point where $\alpha_\omega(t)=0$.

(4) Since experimentally[5] there is a dip or a "break" but not a zero in the angular distribution around $t\sim -0.5$ BeV^2, there should be another contribution present. Since ρ exchange would also yield a zero at the same t value, the only candidate for contributing to $d\sigma/dt$ at $t=-0.5$ is B exchange.[6] An adequate fit of all angular distributions between $E_\gamma=2$ and 5.8 BeV can be achieved with ω and B exchange.[3]

The simple point that we would like to make here is the following: In the $\omega+B$ exchange model, the entire contribution to $d\sigma(\gamma+p\rightarrow\pi^0+p)/dt$ at the point $\alpha_\omega(t)=0$ must come from B exchange and, therefore, from π^0 photoproduction by isoscalar photons. This means that at $t \sim -0.5$ BeV^2, vector dominance gives

$$\frac{d\sigma}{dt}(\gamma+p\to\pi^0+p)_{t=-0.5} = \tfrac{1}{2}g_{\gamma\omega}^2\rho_{11}^H\frac{d\sigma}{dt}(\pi^++n\to\omega+p)_{t=-0.5}, \quad (1)$$

where ρ_{11}^H is the helicity-frame density matrix element for ω production ($\rho_{11}^H \leqslant \frac{1}{2}$), $g_{\gamma\omega}$ is the direct $\omega \to \gamma$ coupling constant, and the factor $\frac{1}{2}$ comes from the isospin relation between the $\pi^0+p\to\omega+p$ and the $\pi^++n\to\omega+p$ cross sections. We have neglected the φ contribution in view of the extremely small $\pi+N\to\varphi+N$ cross section.

Using the measured $\rho^0\to l^++l^-$ decay rate and SU(3), or the vector-dominance predictions, we get[7]

$$g_{\gamma\omega}^2 = (4\pm2)10^{-4}, \quad (2)$$

where the 50% error is probably an overestimate of the actual ambiguities. Using $\rho_{11}^H \leqslant \frac{1}{2}$ we therefore predict

$$\frac{d\sigma}{dt}(\gamma+p\to\pi^0+p)_{t=-0.5} \leqslant 1.5\times10^{-4}\frac{d\sigma}{dt}(\pi^++n\to\omega+p)_{t=-0.5}, \quad (3)$$

where we have used the upper error limit of Eq. (2). A survey of all existing data on $\pi^++n\to\omega+p$ indicates that at $p_{\mathrm{lab}}=6$ BeV/c,[8]

$$40\frac{\mu\mathrm{b}}{\mathrm{BeV}^2} \leqslant \frac{d\sigma}{dt}(\pi^++n\to\omega+p)_{t=-0.5} \leqslant 120\frac{\mu\mathrm{b}}{\mathrm{BeV}^2}, \quad (4)$$

where, again, the error estimate is very liberal. Inserting this value in Eq. (3), we therefore find that vector-dominance and the $\omega+B$ Regge-pole model for π^0 photoproduction predict

$$\frac{d\sigma}{dt}(\gamma+p\to\pi^0+p)_{t=-0.5,\,p_{\mathrm{lab}}=6} \leqslant 0.02\frac{\mu\mathrm{b}}{\mathrm{BeV}^2}, \quad (5)$$

where the right-hand side of the inequality represents an extremely high estimate of the relevant quantity, the actual value being probably around 0.01 $\mu\mathrm{b/BeV}^2$ or less.[9] The experimental values for the left-hand side of Eq. (5) are around 0.1 $\mu\mathrm{b/BeV}^2$ with 20% errors,[5] indicating a discrepancy of at least a factor 4 and probably a factor 10-20 with the $\omega+B$ model.

The moral is that at least 30-50% of the $t=-0.5$ BeV^2 value of $d\sigma(\gamma+p\to\pi^0+p)/dt$ comes from π^0 production by isovector photons, namely from pure $I=0$ exchange, while the rest could come from interference between $I=0$ and $I=1$ exchanges, but probably not from $I=1$ exchange alone. The obvious candidates for the extra $I=0$ exchange term are the elusive ω' meson (if it exists) or the ω-P cut.[10] In the first case, ω' will have to contribute 75-95% of the $t=-0.5$ BeV^2 cross section (unless it finds a ρ' to interfere with; there cannot be ω'-B interference). In the second case, the ω-P cut could interfere with anything (B,ρ',ρ-P cut, etc.). The experimental energy dependence of $d\sigma/dt$ at $t=-0.5$ indicates[5] that $\alpha_{\mathrm{eff}}(-0.5)\approx0$, thus slightly preferring the ω-P cut possibility.

Another interesting consequence of our analysis is the following:

$$\frac{d\sigma}{dt}(\pi^0+p\to\rho^0+p)_{t=-0.5}^{p_{\mathrm{lab}}=6} \geqslant \frac{0.3}{g_{\gamma\rho}^2\rho_{11}^H}\frac{d\sigma}{dt}(\gamma+p\to\pi^0+p)_{t=-0.5}^{p_{\mathrm{lab}}=6}, \quad (6)$$

where the factor 0.3 on the right-hand side follows from the necessity of producing at least 30% of the $t=-0.5$ cross section by isovector photons alone. Using $\rho_{11}^H \leqslant \frac{1}{2}$ and $g_{\rho\gamma}^2=(3.5\pm1)\times10^{-3}$, we predict

$$\frac{d\sigma}{dt}(\pi^0+p\to\rho^0+p)_{t=-0.5}^{p_{\mathrm{lab}}=6} \geqslant 15\frac{\mu\mathrm{b}}{\mathrm{BeV}^2}. \quad (7)$$

At $p_{\mathrm{lab}}=4$ BeV/c the same considerations lead to a lower limit of about 30 $\mu\mathrm{b/BeV}^2$. In terms[11] of measurable cross sections we predict

$$\frac{d\sigma}{dt}(\pi^-+p\to\rho^-+p)+\frac{d\sigma}{dt}(\pi^++p\to\rho^++p)-\frac{d\sigma}{dt}(\pi^-+p\to\rho^0+n)_{t=0.5}^{p_{\mathrm{lab}}=4} \geqslant 60\frac{\mu\mathrm{b}}{\mathrm{BeV}^2}, \quad (8)$$

where the right-hand side is an extremely low estimate. The most probable value for the right-hand side of 100-150 $\mu b/BeV^2$. This is on the border of disagreement with the data collected by Contogouris, Tran Thanh Van, and Lubatti,[11] but we cannot claim a real inconsistency before better data on all the relevant quantities are known. Since pure Reggeized ω exchange predicts a vanishing right-hand side for Eq. (8), our calculation gives a lower limit based on vector dominance for the non-ω contribution to $I=0$ exchange in $\pi N \to \rho N$. Again, an ω' or an ω-P cut are necessary.

We conclude with a few additional remarks:

(a) If the $t=-0.5$ $\gamma+p\to\pi+{}^0p$ cross section comes only from ω' and B exchange, we have seen that the ω' contributes at least 75% of the cross section. This would lead in Eq. (8) to a right-hand side of at least 150 $\mu b/BeV^2$ in contradiction to experiment.[11] This strongly favors the ω-P cut over the ω'.

(b) A good measurement of $d\sigma(\gamma+n\to\pi^0+n)/dt$ will enable us to determine the size and sign of the isovector-isoscalar interference term in π^0 photoproduction. If $\rho+\omega+\omega'+B$ exchange is the correct model, $d\sigma(\gamma+n\to\pi^0+n)/dt = d\sigma(\gamma+p\to\pi^0+p)/dt$, at least at $t=-0.5$ BeV^2 (at other points there could be ρ-ω interference). If the ω-P cut version is favored, $d\sigma(\gamma+n\to\pi^0+n)/dt$ at $t=-0.5$ could be anything between zero and $2d\sigma(\gamma+p\to\pi^0+p)/dt$. The larger the $\gamma+n\to\pi^0+n$ cross section is, the stronger our Eq. (8) becomes, and if we want to minimize the danger of disagreement with the data, we must predict an extremely small and possibly vanishing[12] $\gamma+n\to\pi^0+n$ cross section at $t=-0.5$.

(c) Polarized-photon experiments may, in principle, distinguish between ω' exchange and an ω-P cut contribution to π^0 photoproduction. The ω' involves only natural parity exchange, while the ω-P cut could a priori contribute to the exchange of natural and unnatural parity.[13]

(d) The small isoscalar-photon contribution to π photoproduction at $t=-0.5$ is sufficient to induce the large observed π^+/π^- ratio in $\gamma+d\to N+N+\pi$, if it interferes strongly with the isovector contribution to charged π photoproduction. This can happen through π-B interference or through any number of cut-pole interference effects.

(e) Vector dominance and the measured π^+/π^- photoproduction ratio predict a sharp forward peak in $\rho_{11}{}^H d\sigma(\pi+N\to\rho+N)/dt$ in all possible charge states except $\pi^0\to\rho^0$, and a forward dip in $\rho_{11}{}^H d\sigma(\pi+N\to\omega+N)/dt$. No significant data are available.

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*Work supported in part by the U. S. Atomic Energy Commission.

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[7]$\Gamma(\rho\to l^++l^-)/\Gamma(\rho\to\pi^++\pi^-)=(5\pm1.5)\times10^{-5}$ is a reasonable average of present data. [See, e.g., S. C. C. Ting, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies Stanford, California, 1967 (Clearing House of Federal Scientific and Technical Information, Washington, D.C.).] It leads to $g_{\gamma\rho}{}^2=(3.5\pm1)\times10^{-3}$. SU(3) predicts $g_{\gamma\omega}{}^2=\frac{1}{9}g_{\rho\gamma}{}^2\sim4\times10^{-4}$. Vector dominance and the experimental $\Gamma(\omega\to\pi^0+\gamma)/\Gamma(\pi^0\to2+\gamma)$ gives values around $g_{\gamma\omega}{}^2=5\times10^{-4}$.

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CERN, 1968 (to be published), Vol. II, p. 135, find at $p_{lab} = 5.1$ BeV/c,

$$\sigma(\pi^+ + n \to \omega + p) \times \frac{\Gamma(\omega \to \pi^+ + \pi^- + \pi^0)}{\Gamma(\omega \to \text{all})} = 128 \pm 3\ \mu\text{b},$$

with a t dependence e^{Bt}, $B = 3.08 \pm 0.7$. Using the known $\omega \to \pi^+ + \pi^- + \pi^0$ branching ratio we estimate

$$\frac{d\sigma}{dt}(\pi^+ + n \to \omega + p)_{t=-0.5}^{p=5.1} = 100 \pm 50\ \frac{\mu\text{b}}{\text{GeV}^2}.$$

Assuming an $s^{2\alpha-2}$ energy dependence with $-\frac{1}{2} < \alpha < \frac{1}{2}$, we find at $p_{lab} = 6$ BeV and $t = -0.5$ a value of 80 ± 40 μb/GeV^2. Barmawi (Ref. 2) quotes experiments of W. Bugg et al. and G. Benson et al. giving $d\sigma/dt \sim 0.25$ mb/GeV^2 at $t = -0.5$, $p_{lab} = 3.25 - 3.65$ BeV/c. Assuming the same energy dependence as above we find for $p_{lab} = 6$ GeV/c and $t = -0.5$, $d\sigma/dt \sim 80 \pm 30$ μb/GeV^2. E. Shibata and M. Wahlig, Phys. Letters 22, 354 (1966) find at $p_{lab} = 10$ BeV/c,

$$\sigma(\pi^- + p \to \omega^0 + n) \times \frac{\Gamma(\omega \to \pi + \gamma)}{\Gamma(\omega \to \text{all})} = 5 \pm 2\ \mu\text{b}$$

with an e^{4t} t dependence. This gives at $t = -0.5$, $d\sigma/dt = 20 \pm 10$ μb/GeV^2. The same energy correction gives at $p_{lab} = 6$ and $t = -0.5$, $d\sigma/dt = 60 \pm 45$ μb/GeV^2. The consistency among these evaluations encourages us in believing that our Eq. (4) is realistic.

[9]In addition to taking the extreme limits of Eqs. (2) and (4), we have also used the $\rho_{11} = \frac{1}{2}$ limit in the absence of concrete information. The average values of Eqs. (2) and (4) and a $\rho_{11} \sim \frac{1}{4}$ would give 0.004 μb/GeV^2 as the limit in Eq. (5).

[10]The ω' may be needed elsewhere in order to avoid the difficulty with factorization pointed out by V. Barger and L. Durand, Phys. Rev. Letters 19, 1295 (1967).

[11]A. P. Contogouris, J. Tran Thanh Van, and H. J. Lubatti, Phys. Rev. Letters 19, 1352 (1967).

[12]This agrees with the prediction of Dar et al., Ref. 1, who derived it using different assumptions.

[13]One could also consider the exchange of the $I = 0$ component of the B-meson octet. Such a contribution would interfere with B exchange but not with ω'. Polarized-photon experiments can distinguish between such a contribution and ω' exchange. Another possibility is the introduction of a fixed pole, either in photoproduction only or in photoproduction and $\pi + N \to V + N$.

PERTURBATION METHOD FOR ATOMS IN INTENSE LIGHT BEAMS

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(Received 12 August 1968)

The problem of interaction of atoms with intense light is reformulated via a time-dependent unitary transformation. An effective electronic binding potential is obtained. The effective perturbation remains bounded as the intensity of the incident light increases.

The mechanism responsible for initiating sparking in gases irradiated by very intense laser beams (about 10^{11} W/cm^2) is usually considered to be multiphoton photoeffect. Past calculations of ionization cross sections have been low by many orders of magnitude, and calculations of threshold intensities have been high by two orders of magnitude.[1,2] The difficulty experienced in these calculations is that perturbation theory is applied to intensities far beyond the limit of validity of the usual theory, and what is equally important, the effect of the intense electromagnetic wave on the initial state has been totally neglected. Indeed, the concept of photon absorption has its roots in perturbation theory, so that even the meaning of the concept becomes unclear at the intensities that we consider.

In view of these difficulties, we propose a reformulation of the problem of the interaction of intense light with atoms. Essentially, the method consists of a transformation to an accelerated frame of reference. It is shown that, in nonrelativistic dipole approximation, an effective intensity-dependent potential that binds the electrons can be found. The remaining terms in the interaction approach a finite limit as the incident intensity is increased. The present formulation of the problem is equivalent to the usual one at low intensities.

For simplicity, we consider a hydrogen atom in the nonrelativistic dipole approximation. The method is easily generalized to the case of many electrons moving in a Coulomb potential. The Schrödinger equation is

$$\frac{1}{2m}\left[\frac{\hbar}{i}\vec{\nabla} - \frac{e}{c}\vec{A}(t)\right]^2 \Psi(\vec{r}, t) + V(\vec{r})\Psi(\vec{r}, t) = i\hbar\frac{\partial \Psi}{\partial t}(\vec{r}, t). \qquad (1)$$