Regge-Pole Model with Absorptive Correction Cuts for π^0 Photoproduction*

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A Regge-pole model with ω- and B-meson exchange and absorptive corrections for π^0 photoproduction on protons is reported. The calculation fits existing data between 3 and 16 GeV fairly well. Further experimental checks of the model are suggested.

A CONSIDERABLE number of data on forward photoproduction of π^0 mesons at energies up to 6 GeV have been obtained in the last three years by groups at DESY[1] and at CEA.[2] These data have been successfully interpreted in terms of a model involving Reggeized ω- and B-meson exchange.[3] The ω exchange accounts for most of the cross section, but ω exchange alone would give a zero in the cross section near $(-t)=0.5$ GeV^2, where the ω trajectory goes through zero. B-meson exchange fills in this dip, but with a B trajectory lying below the ω trajectory, as has been used in the fits of these data, the dip in the cross section near $(-t)=0.5$ GeV^2 should become deeper as the energy increases. Recently, an experiment has been reported by a SLAC group[4] which extends the range over which the π^0 cross section has been measured up to 16-GeV photon energy. Whereas the lower-energy experiments cover the region of very small momentum transfer, the measurements at the higher energies are only above $(-t)=0.2$ GeV^2. The data at 6 GeV and below show a dip around $-t=0.5$ GeV^2 but at $E_\gamma=11$ and at 16 GeV there seems to be no dip at all. Furthermore, if one looks at all the π^0 data by plotting $(s-m^2)^2 d\sigma/dt$ versus $-t$, the experimental results seem to show almost no energy dependence up to rather appreciable momentum transfers. This is consistent with the exchange of an effective Regge trajectory with small slope and an intercept near zero. If the data exhibit any energy dependence at all, the dip region varies the most strongly. This behavior of $d\sigma/dt$ with energy seems incompatible with the simple model based on Reggeized ω exchange. Of course, if a large amount of B exchange is present, the energy dependence may be different, and be compatible with the data. However, a model with an appreciable B-exchange contribution is ruled out by a recent measurement of the cross section for $\gamma p \rightarrow \pi^0 p$ with polarized photons with an energy of 3 GeV at CEA.[5] The results of this experiment[6] show that at the point where the ω trajectory goes through zero the asymmetry ratio $\Sigma=(\sigma_\perp-\sigma_\parallel)/(\sigma_\perp+\sigma_\parallel)$ is roughly 0.5. This implies that $\sigma_\perp/\sigma_\parallel \simeq 3$, i.e., the cross section is dominated by natural spin-parity exchange.[7] It has been emphasized recently by Richter[6] that these three experimental facts, the disappearance of the dip at high energies, the energy independence of $(s-m^2)^2 d\sigma/dt$ as far as it is measured, and the ratio of $\sigma_\perp/\sigma_\parallel$ in the dip region put the Regge-pole model based on ω- and B-meson exchange alone in reasonable doubt.

In the last two years, some authors have tried successfully to supplement Regge-pole models with cut contributions generated from absorptive corrections.[8] The absorptive contributions add terms that are logarithmically dependent on energy compared to the pure Regge-pole terms (like genuine cuts in the angular momentum plane). It is clear that the cut terms generated from absorption can fill in dips, and give both natural and unnatural parity contributions to generate asymmetries and polarizations.

In this note, we report about a search to explain all available π^0 photoproduction data in terms of a Regge-pole model based on ω, ρ, and B exchange, supplemented with absorptive corrections of reasonable strength. It is not our intention to present an accurate fit to the

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[1] M. Braunschweig, W. Braunschweig, D. Husmann, K. Lübelsmeyer, and D. Schmitz, Phys. Letters **26B**, 405 (1968).

[2] G. C. Bolon, D. Garelick, S. Homma, R. Lewis, W. Lobar, D. Luckey, L. S. Osborne, R. Schwitters, and J. Uglum, Phys. Rev. Letters **18**, 926 (1967).

[3] J. P. Ader, M. Capdeville, and Ph. Salin, Nucl. Phys. **33**, 407 (1967). See also Ref. 1.

[4] R. Anderson, D. Gustavson, J. Johnson, D. Ritson, W. G. Jones, D. Kreinick, F. Murphy, and R. Weinstein, Phys. Rev. Letters **21**, 384 (1968).

[5] D. Bellenger, R. Bordelon, K. Cohen, S. Deutsch, W. Lobar, D. Luckey, L. S. Osborne, E. Pothier, and R. Schwitters, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN Scientific Information Service, Geneva, Switzerland, 1968), paper No. 530.

[6] The results of this experiment are reported by B. Richter, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 3.

[7] P. Stichel, Z. Physik **180**, 170 (1964).

[8] R. C. Arnold, Phys. Rev. **153**, 1523 (1967); Argonne Report No. ANL/HEP 6804, 1968 (unpublished); G. Cohen-Tannoudji, A. Morel, and H. Navelet, Nuovo Cimento **48A**, 1075 (1967); J. N. J. White, Phys. Letters **26B**, 461 (1968); F. Schrempp, Nucl. Phys. **B6**, 487 (1968); R. C. Arnold and M. L. Blackmon, Phys. Rev. **176**, 2082 (1968); M. L. Blackmon and G. R. Goldstein, *ibid.* **179**, 1480 (1969); M. L. Blackmon, *ibid.* **178**, 2385 (1969).

data, but rather to study qualitatively whether the three experimental facts mentioned above, which are in conflict with pure ω-, B-exchange models, can be reconciled with an ω-, B-exchange model including cuts.

Our calculations are based on Reggeized Chew-Goldberger-Low-Nambu (CGLN) amplitudes A_1, A_2, A_3, and A_4 as worked out by several authors some years ago.[9] The nonvanishing amplitudes for ω (ρ) and B exchange have been parametrized as follows

(1) ω (ρ) exchange:

$$A_1=-\frac{\pi\alpha'}{\sin\pi\alpha}\frac{1-e^{-i\pi\alpha}}{2\Gamma(\alpha+1)}\left(\frac{s-u}{2s_0}\right)^{\alpha-1}(-t)\frac{f_{2\omega}}{2m}\lambda_\omega\,,$$

$$A_2=-(1/t)A_1\,, \qquad (1)$$

$$A_4=-\frac{\pi\alpha'}{\sin\pi\alpha}\frac{1-e^{i\pi\alpha}}{2\Gamma(\alpha+1)}\left(\frac{s-u}{2s_0}\right)^{\alpha-1}f_{1\omega}\lambda_\omega\,.$$

Here the residue for ω exchange is factored into $f_{1\omega}$ and $f_{2\omega}$, which are the Dirac and Pauli coupling constants, respectively, and λ_ω is the $\gamma\omega\pi$ coupling. Similar equations hold for the ρ-exchange amplitude. α' is the derivative of the trajectory at the ω (ρ) mass and m is the nucleon mass. In this ansatz, the ω (ρ) trajectory chooses the nonsense mechanism. The extra factor $(-t)$ in A_1 is necessary to prevent a pole for $t=0$ in the amplitude A_2.

(2) B exchange:

$$A_2=-\frac{\pi\alpha'}{\sin\pi\alpha}\frac{1-e^{-i\pi\alpha}}{2\Gamma(\alpha+1)}\left(\frac{s-u}{2s_0}\right)^{\alpha-1}\frac{f_B}{2m}\lambda_B\,. \qquad (2)$$

With the invariant amplitudes determined by (1) and (2) the s-channel helicity amplitudes are easily calculated and from them s-channel partial-wave amplitudes are obtained. These are corrected with absorption factors in the initial and final state.[10] The absorption parameter C and the parameter $f_{\rho\pi\pi}(g'/e)$ which determines the proportion of initial- to final-state absorption, both being defined in Ref. 10, have been chosen to $C=0.9$, and $f_{\rho\pi\pi}(g'/e)=1$. $C=0.9$ corresponds to 30% more absorption than one would infer from the value of the total pion-nucleon cross section above 4 GeV. The desirability of increasing the strength of the absorption has been noticed previously. This effect can be due to the contribution of inelastic states or, as noted in work on elastic πN and KN scattering,[8] the eikonal model gives an absorption which is larger than the value obtained from σ_T. We therefore feel that $C=0.9$ is quite reasonable. The value $f_{\rho\pi\pi}(g'/e)=1$ is the pure vector-dominance limit.

[9] G. Kramer and P. Stichel, Z. Physik **178**, 519 (1964); G. Zweig, Nuovo Cimento **32**, 689 (1964); R. W. Childers and W. G. Holladay, Phys. Rev. **132**, 1809 (1963).

[10] G. Kramer, K. Schilling, and L. Stodolsky, Nucl. Phys. **B5**, 317 (1968). Earlier papers using absorption in photoproduction processes are given in this reference.

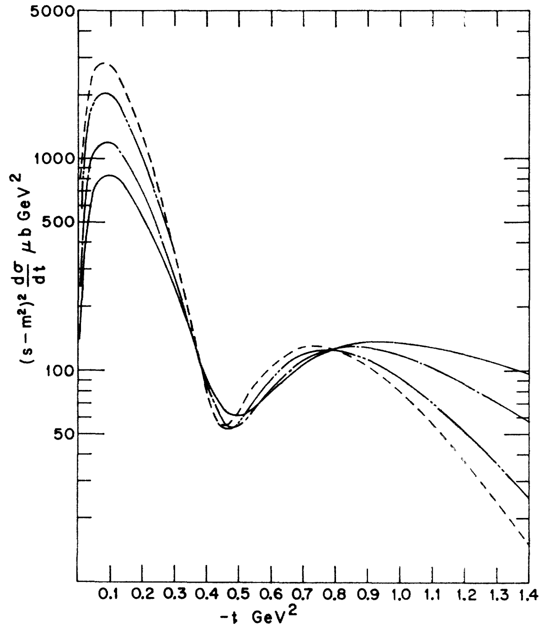

FIG. 1. Differential cross sections for $\gamma p \to \pi^0 p$ based on ω- and ρ-meson exchange including initial- and final-state absorption for $E_\gamma=4$ (solid line), 6 (dash-dot), 11 (dash-dot-dot), and 16 (dash) GeV. The cross sections are not normalized to the measured cross sections. The curves shown correspond to $f_{1\rho}=13.57$.

Besides ω- and B-meson exchange, the ρ^0 can also contribute to π^0 photoproduction. It is generally assumed that the $\gamma\rho\pi$ coupling is smaller by a factor of 3, compared to the $\gamma\omega\pi$ coupling, and that $f_{1\rho}$ is also smaller than $f_{1\omega}$. On the other hand, from analysis of π-N charge exchange it is known that the ρ has a large anomalous moment coupling to the nucleon. Therefore, we also take into account ρ exchange and fix the relative sizes of the coupling constants in accordance with the usual SU_6 (or quark model) relation $f_{1\omega}=3f_{1\rho}$, $\lambda_\omega=3\lambda_\rho$. The trajectory of the ρ is well known from π-N charge-exchange analysis and is taken as $\alpha_\rho=0.50+0.79t$.[11] The ω trajectory is $\alpha_\omega=0.45+0.9t$ which is roughly the same as has been used in analyses of other processes based on Regge poles and absorptive correction cuts.[12] Furthermore, we put $f_{2\rho}/f_{1\rho}=11.8$,[11] $f_{2\omega}=0$, and $s_0=1$ GeV^2.

To see the effect of the absorption on the ω and ρ, both of which have natural parity, we calculated $(s-m^2)^2 d\sigma/dt$ for the energies $E_\gamma=4$, 6, 11, and 16 GeV and the asymmetry $\Sigma=(d\sigma_\perp/dt-d\sigma_\parallel/dt)/(d\sigma_\perp/dt+d\sigma_\parallel/dt)$ for three representative energies $E_\gamma=3$, 4, and 16 GeV. The results are shown in Figs. 1 and 2. We observe that the absorption effects fill in the dip but that $(s-m^2)^2 d\sigma/dt$ is roughly independent of energy in the dip region and around the second maximum for the

[11] F. Schrempp, Ref. 8; R. C. Arnold and M. L. Blackmon, Ref. 8.

[12] M. L. Blackmon and G. R. Goldstein, Ref. 8.

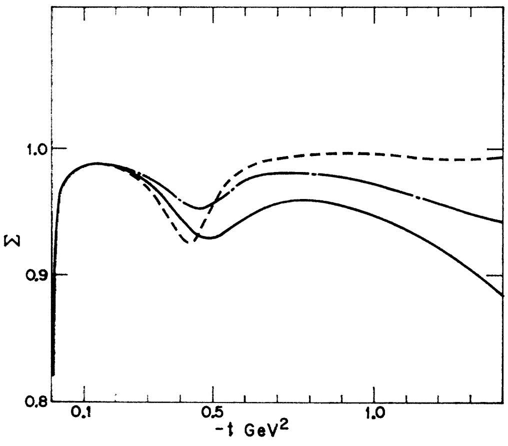

FIG. 2. π^0 photoproduction cross sections with polarized photons: $\Sigma=(d\sigma_\perp/dt-d\sigma_{\parallel}/dt)/(d\sigma_\perp/dt+d\sigma_{\parallel}/dt)$ for $E_\gamma=3$ (solid line), 4 (dash-dot), and 16 (dash) GeV for the same model as in Fig. 1.

energy range considered.[13] Since the experimental data show that the dip disappears with increasing energy, ω and ρ exchange plus their absorption-cut contributions are not sufficient. This can also be inferred from the asymmetry shown in Fig. 2. The absorption effects to ω and ρ produce some unnatural-parity contributions around $-t=0.5$ GeV^2 but not enough to account for the observed asymmetry, which is as low as 0.4 at $-t=0.7$ GeV^2 for $E_\gamma=3$ GeV.[5,6,14] Therefore, a trajectory with unnatural parity is needed to account for the minimum in Σ for $E_\gamma=3$ GeV. It must have negative C parity and couple to the photon and the pion. The only candidate available is the B meson. There is no experimental evidence for the trajectory of the B, although recent theoretical investigations of Regge-behaved crossing-symmetric amplitudes indicate that the slope of Regge trajectories might be universal.[15] We find that a B trajectory with slope about 0.9 GeV^{-2} will not fill in the dip near $\alpha_\omega=0$, and so we must choose a small slope, thus giving a rather high-lying trajectory: $\alpha_B=0.4+0.4t$. With coupling constants $f_{1\rho}=4.88$ and λ_ρ determined in such a way that $\Gamma(\rho\to\pi\gamma)=0.13$ MeV, $\lambda_B f_B=-30$ GeV^{-1}, we computed $d\sigma/dt$ for the lower energies $E_\gamma=3$, 4, 5, and 5.8 GeV shown in Fig. 3, together with the experimental data from DESY and CEA.[1,2] The results for $(s-m^2)^2 d\sigma/dt$ at $E_\gamma=4$, 6, 11, and 16 GeV are compared with the DESY[1] and SLAC[4] data in Fig. 4. The asymmetry, calculated for $E_\gamma=3$, 4, 6, and 16 GeV, is given together with the CEA data at $E_\gamma=3$ GeV [5,6] in Fig. 5. The fit to the low-energy cross sections $d\sigma/dt$ is reasonably good and somewhat better than the old $\omega+B$ models without absorption.[1] The asymmetry data are not completely reproduced. The minimum of the theoretical curve is lower and shifted to a smaller $|t|$ value if compared to the measurements. The energy dependence of $(s-m^2)^2 d\sigma/dt$ between 4 and 16 GeV is roughly reproduced by our model up to the highest $|t|$ values measured. The energy spread of the data around $-t=0.6$ GeV^2 is somewhat larger than what the theoretical curves show, but still roughly compatible inside the errors. The data seem to indicate that $(s-m^2)^2 d\sigma/dt$ for $E_\gamma=6$ GeV is smaller at $-t=0.5$ GeV^2 than the same quantity for $E_\gamma=4$ GeV. This behavior is not seen in the theoretical curves, but data with higher accuracy are needed before a clear discrepancy can be established. Since we have chosen for the ω- and B-meson trajectories an intercept around 0.4, the cross section $(s-m^2)^2 d\sigma/dt$ has its largest s dependence in the forward momentum-transfer region below $-t=0.2$ GeV^2. In this region only one measurement has been made at $E_\gamma=11$ GeV and $-t=0.2$ GeV^2. The experimental point is about three standard deviations from our theoretical curve for $E_\gamma=11$ GeV. Any claim that $(s-m^2)^2 d\sigma/dt$ is

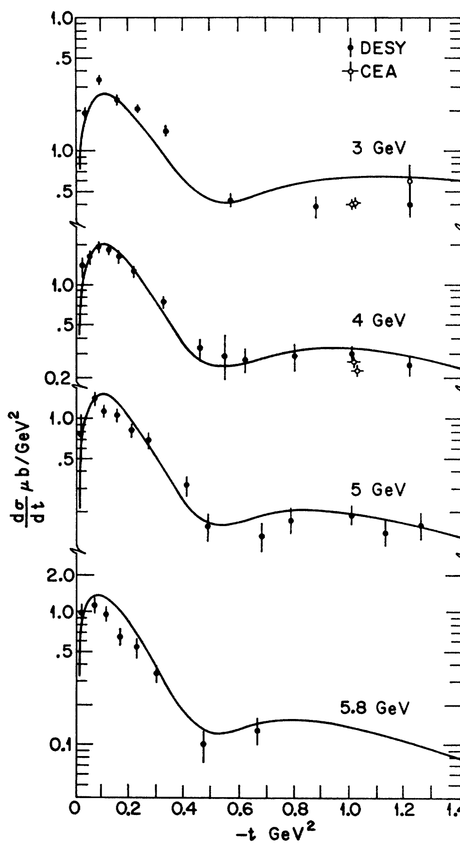

FIG. 3. Differential cross sections for $\gamma p\to\pi^0 p$ based on ω-, ρ-, and B-meson exchange including absorption effects for $E_\gamma=3$, 4, 5, and 5.8 GeV, as described in the text. The experimental points are from Refs. 1 and 2.

[13] This behavior of $(s-m^2)^2 d\sigma/dt$ does not change appreciably if we increase the absorption to $C=1.5$. Then the minimum is somewhat shifted to smaller $-t$ values, but $(s-m^2)^2 d\sigma/dt$ is still constant in s around the minimum and second maximum between 6 and 16 GeV.

[14] If C is again increased to $C=1.5$, the minimum of Σ near $-t=0.5$ GeV^2 is decreased, but at $E_\gamma=6$ GeV, for instance, Σ_{min} changes only to $\Sigma_{min}=0.91$ at $-t=0.32$ GeV^2, instead of $\Sigma_{min}=0.96$ at $-t=0.44$ GeV^2 for $C=0.9$.

[15] M. Ademollo, G. Veneziano, and S. Weinberg, Phys. Rev. Letters 22, 83 (1969); C. J. Goebel, M. L. Blackmon, and K. C. Wali, Phys. Rev. (to be published).

independent of energy for small t can rely only on this one point. Clearly, extensions of the high energy measurements into the momentum-transfer region around $-t=0.1$ GeV^2 could settle the question whether the ω trajectory has a form as currently believed, and assumed in this calculation. The energy dependence of the asymmetry is also interesting. In our model, the B-meson contribution becomes more and more important with increasing energy in the dip region around $-t=0.5$ GeV^2. Therefore, the minimum in the asymmetry Σ increases with s, and Σ eventually turns negative. Measurements of Σ for energies around $E_\gamma=10$ GeV would be very helpful to prove or disprove our ω-B interference model. For the ω- and B-meson trajectories that we have chosen, the absorption is essential in order to fit the asymmetry Σ for $E_\gamma=3$ GeV. With no absorption, our choice of parameters gives $\Sigma_{\min}=-0.7$ near $-t=0.5$ GeV^2, even for $E_\gamma=3$ GeV. This behavior is to be expected since the ρ contribution we introduced is not strong enough to overcome the unnatural-parity

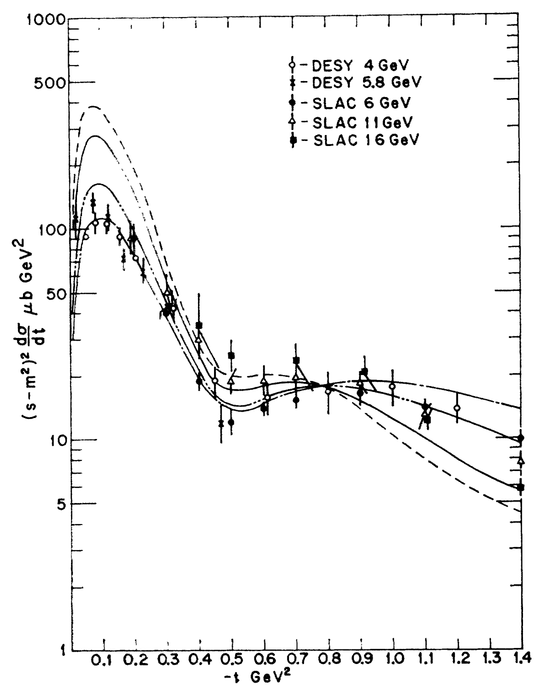

FIG. 4. π^0 photoproduction cross section for $E_\gamma=4$ (dash-dot), 6 (dash-dot-dot), 11 (solid), and 16 (dash) GeV for the ω-, ρ-, and B-meson model compared to the data of Refs. 1 and 4.

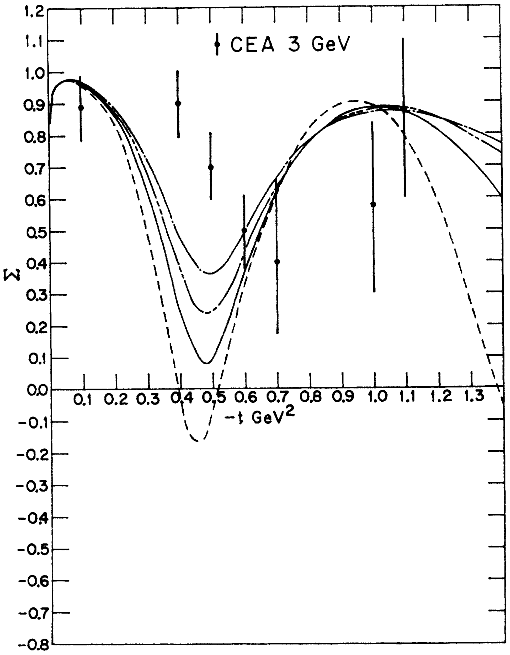

FIG. 5. Asymmetry Σ for $E_\gamma=3$ (dash-dot), 4 (dash-dot-dot), 6 (solid), and 16 (dash) GeV for the same model as Fig. 3 and Fig. 4. The experimental data are for $E_\gamma=3$ GeV and are from Ref. 6.

contribution of the B meson near $\alpha_\omega=0$. Therefore, we suspect that without absorption it is impossible to fit the asymmetry parameter Σ near $\alpha_\omega=0$ and simultaneously to make the dip in the cross section go away for high energies. Furthermore, in π^0 photoproduction on neutrons $\gamma+n\to\pi^0+n$, the interference between the ω and its cut on one side and the ρ- and B-meson contribution and their cuts on the other side has the opposite sign compared to $\gamma+p\to\pi^0+p$. Therefore, measurements of $\gamma+n\to\pi^0+n$ would be very helpful to establish the isospin content of the amplitudes which interfere with the ω and its cut. The B meson contributes to the isoscalar part of the photoproduction amplitude. Therefore, it will cause a difference in the cross sections for $\gamma+p\to\pi^++n$ and $\gamma+n\to\pi^-+p$. Since for the moment we have no reliable model based on Regge exchanges and absorption which describes the isovector part for these two reactions, we do not know whether our choice of B-meson parameters can account for the observed difference in $\pi^\pm$ photoproduction cross sections.