PION PHOTOPRODUCTION AT 0°†

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The special features of forward pion photoproduction at high energies are discussed. It is established that the cross section for single pion production can generally be expected to have a forward dip barring a conspiracy between Regge trajectories. Photoproduction of the A_1 (1^+) meson followed by its decay is suggested as an important source of high-energy forward pions.

Forward photopion production at high energies has simple features of special interest. Real photons, being transversely polarized, introduce into the production amplitude a unit of (spin) angular momentum along their direction of motion. This unit of spin cannot be carried off by a zero-spin pion produced at precisely the forward angle $\theta = 0°$ since its orbital angular momentum is normal to its direction of motion. A unit of spin must therefore be transmitted to the target. This requirement suppresses the contribution at $\theta = 0°$ of the t-channel exchanges that are normally assumed to dominate the high-energy, low-momentum-transfer behavior of this process.

We may thus hope to learn interesting, new, and unusual aspects of photoproduction by studying the processes leading to a pion at $\theta = 0°$. To be more precise, we are interested in production angles $\theta < \theta_p = \mu/\omega$ which is the characteristic angle for the peripheral photoproduction events leading to pions of mass μ and energy ω; here ω is a large fraction of the photon energy k.

Earlier experiments[1] on photoproduction up to photon energies $k \sim 6$ BeV have consistently indicated appreciable pion fluxes at angles $\theta < \theta_p$ at variance with all theoretical models[2] which predict a dip in the angular distribution in the region of $\theta < \theta_p$. More recently the beam-survey measurements[3] at Stanford Linear Accelerator Center (SLAC) have confirmed and extended these observations to higher energies. These results have triggered this investigation[4] which will show the following:

(a) In a Regge-pole theory analysis, the amplitude for single-pion production at high energy will have a dip in its angular distribution at forward angles $\theta < \theta_p$; only contributions from contact interactions or s-channel pole terms can escape this dip. Since such contributions lie outside the Regge-pole model, we expect them to play a relatively minor role.

(b) Decay pions from the dominant channel of vector-meson production (ρ^0 production) generally exhibit such a dip.[5] Pions from ω^0 can appear in the forward direction; however, this process cannot fill up the dip in the pion distribution since the ω^0's are only weakly produced relative to the ρ^0's at high energies.

(c) The least massive state which might be strongly produced and subsequently decay to pions which escape such a dip is A_1 photoproduction followed by the decay chain

$$A_1 \to \rho + \pi; \quad \rho \to \pi + \pi.$$

A number of experimental predictions can be based on the assumption that this is an important channel leading to pions at angle $\theta < \theta_p$. (Similar remarks apply also to A_2 production followed by the same decay chain.)

We begin by analyzing the photoproduction of a single pion by t-channel exchanges of Regge families of zero baryon number [generalized peripheral model— Fig. 1(a)]. Charge labels are suppressed except where necessary. We use the invariant variables $s = (p+k)^2$, $t = (k-q)^2$, where m = nucleon mass and μ = pion mass, as well as the laboratory variables (k, ω, q, θ) = (photon energy, pion energy, pion momenta, production angle). ϵ_μ denotes the photon polarization and we find it convenient to work

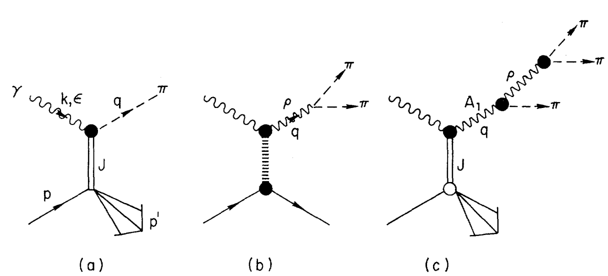

FIG. 1. Photoproduction of (a) single pions via spin-J exchange; (b) ρ^0 mesons via diffraction; (c) A_1 mesons via spin-J exchange.

in transverse gauge $\epsilon_\mu = (0, \vec{\epsilon})$. At the high energies, $k \gg m$, and small angles of interest here we have $-t \cong k^2\theta^2 + \mu^4/2k^2$.

For the exchange of abnormal-parity states, $P = -(-1)^J$, the upper vertex in Fig. 1(a) has the following gauge-invariant form[6] ($J > 0$):

$$V \sim (\epsilon_{\mu_1} k\cdot q - \epsilon\cdot q k_{\mu_1}) K_{\mu_2} \cdots K_{\mu_J} \psi^{\mu_1 \cdots \mu_J};$$
$$K = k + q, \tag{1}$$

where $\psi^{\mu_1 \cdots \mu_J}$ is the totally symmetric Rarita-Schwinger wave function for a particle of spin J. The crucial point is that the photon wave function, being antisymmetric under $\mu \leftrightarrow \nu$ interchange, cannot have both of its indices contracted with those of the symmetric wave function $\psi^{\mu_1 \cdots \mu_J}$. Independent of what happens at the lower vertex in Fig. 1(a), the first term in Eq. (1), though nonzero in the forward direction, is reduced in magnitude by a full power of s because of the momenta used up in forming the factor $k\cdot q = (\mu^2 - t)/2 \cong (\mu^2 + k^2\theta^2)/2$. The second term in Eq. (1) does not suffer this suppression in s but vanishes at $\theta = 0$ since

$$-\epsilon\cdot q = \vec{\epsilon}\cdot\vec{q} \approx q\theta. \tag{2}$$

Thus we conclude for abnormal-parity exchange that there will be a dip in the amplitude $A(k, \theta)$ of single-pion production as we decrease θ from $\theta \sim \theta_p$ to $\theta \sim 0°$, such that

$$\frac{A(k, \theta\sim 0°)}{A(k, \theta\sim\theta_p)} \lesssim \mu/\omega. \tag{3}$$

For normal-parity exchange, $P = (-1)^J$, the upper vertex in Fig. 1(a) is ($J > 0$)

$$\tilde{V} \sim \epsilon_{\mu_1 \nu\kappa\sigma} \epsilon^\kappa k^\sigma q^\nu K_{\mu_2} \cdots K_{\mu_J} \psi^{\mu_1 \cdots \mu_J} \tag{4}$$

and the conclusion of a dip, Eq. (3), again applies. This is apparent from the form of Eq. (4). Because of the presence of the antisymmetric $\epsilon_{\mu_1 \nu\kappa\sigma}$ in Eq. (4), the vertex is proportional to $(k^\sigma q^\nu - k^\nu q^\sigma)$ which at high energies and small angles is protected from vanishing only by the pion mass.

The exchange of the pion itself requires special treatment. The photon coupling to the pion current via the vector potential $A_\mu \sim \epsilon_\mu$ is not gauge invariant by itself. To maintain gauge invariance, one must also include the s-channel contribution of the nucleon current. In perturbation theory for $\gamma + p \to \pi^+ + n$, one has the amplitude

$$A \sim e g_{\pi NN} \bar{u}(p')\gamma_5 \left\{\frac{\epsilon\cdot q}{k\cdot q} - \frac{\epsilon\cdot p}{k\cdot p} - \frac{i\sigma_{\mu\nu}}{2k\cdot p}\epsilon^\mu k^\nu\right\} u(p). \tag{5}$$

The first term of Eq. (5) comes from pion exchange, the second and third terms come from the s-channel nucleon Born diagram. The gauge-invariant convection-current part of Eq. (5), $(\epsilon\cdot q/k\cdot q - \epsilon\cdot p/k\cdot p)$, vanishes in the forward direction by Eq. (2) and since $\epsilon\cdot p = 0$ (transverse gauge in lab).

The remaining part of Eq. (5) has no forward dip and gives in the nonrelativistic limit the Kroll-Ruderman theorem for the threshold s-wave photoproduction of π^+. However, such a $\gamma_5 \sigma_{\mu\nu}\epsilon^\mu k^\nu$ contact term describes the emission of pions in low (s and p) waves only. In the conventional Regge-peripheral view one considers that high-energy reactions proceed via the cumulative effect of many high partial waves (large impact parameters) and that production in low partial waves plays a relatively minor role, being severely suppressed by absorption mechanisms. Hence, we do not feel that such contact terms will be important at high energies. Analogous contact terms can be present in pure strong-interaction processes; experience seems to indicate that they are not important.

In the spirit of this philosophy we thus conclude as a general result that a forward dip must occur in the high-energy production of single pions. Having arrived at this for arbitrary spin and parity exchange, we can therefore apply this conclusion to arbitrary Regge-trajectory exchange.[7]

In search of processes leading to copious production of pions at $\theta \to 0°$, we turn next to photoproduction of mesons with spin which subsequently decay to pions. The first candidate is vector-meson photoproduction. It is now well established experimentally[8] that coherent ρ^0 photoproduction, Fig. 1(b), is the dominant channel in the multi-BeV region (3 BeV $< k <$ 6 BeV); we may therefore treat ω and φ as being of secondary importance.

Rho mesons coherently produced at 0° are transversely polarized and cannot, therefore, decay to forward pions. The detailed calculations of Tsai,[9] who considered also nonzero ρ photoproduction angles and integrated over the second pion emerging in the decay $\rho^0 \to \pi^+ + \pi^-$, indicates that the node at $\theta = 0°$ is only partially filled and that an appreciable dip still persists. In $\rho^{\pm}$ as well as incoherent ρ^0 production the assumption of only t-channel exchanges leads also to the same conclusion as above of a forward dip in pion production (see the discussion of 1^+ production below). The key point is that at high energies the ρ in and near the forward direction is produced with transverse polarization (the longitudinal state is suppressed by a power of s) and hence cannot decay to a forward pion.

We turn now to the photoproduction of A_1 (1^+) mesons, Fig. 1(c). Denoting the polarization vector of the A_1 by e, we write the three possible couplings of a photon, A_1, and a spin-J^A (abnormal-parity) particle[10]:

$$V_1 \sim (\epsilon\cdot q\, k\cdot e - k\cdot q\, \epsilon\cdot e)K_{\mu_1}\cdots K_{\mu_J}\psi^{\mu_1\cdots\mu_J},\quad J\geq 0;$$

$$V_2 \sim (\epsilon_{\mu_1}k\cdot q - k_{\mu_1}\epsilon\cdot q)e_{\mu_2}K_{\mu_3}\cdots K_{\mu_J}\psi^{\mu_1\cdots\mu_J},\quad J\geq 2;$$

$$V_3 \sim (\epsilon_{\mu_1}k\cdot e - k_{\mu_1}\epsilon\cdot e)K_{\mu_2}\cdots K_{\mu_J}\psi^{\mu_1\cdots\mu_J},\quad J\geq 1. \tag{6}$$

In the forward direction at high energy the only important contribution comes from V_3 (magnetic dipole):

$$V_3 \sim -(\epsilon_{\mu_1}k\theta - k_{\mu_1}\vec{\epsilon}\cdot\vec{e})K_{\mu_2}\cdots K_{\mu_J}\,\psi^{\mu_1\cdots\mu_J}\text{ for transverse }\vec{e},$$

$$\sim -\tfrac{1}{2}\epsilon_{\mu_1}m_{A_1} + k_{\mu_1}\omega\theta/m_{A_1}K_{\mu_2}\cdots K_{\mu_J}\psi^{\mu_1\cdots\mu_J}\text{ for longitudinal }\vec{e}. \tag{7}$$

For normal-parity exchange (J^V) the vertices $\tilde{V}_{1,2,3}$ are obtained from Eq. (6) by the replacement $\epsilon_\mu k_\nu - \epsilon_\nu k_\mu \to \epsilon_{\mu\nu\kappa\sigma}\epsilon^\kappa k^\sigma$. The dominant term is (electric dipole)

$$\tilde{V}_3 \sim +g_{\mu_1 0}\vec{k}\cdot(\vec{e}\times\vec{\epsilon}) + g_{\mu_1 j}(\vec{e}\times\vec{\epsilon})^j kK_{\mu_2}\cdots K_{\mu_J}\psi^{\mu_1\cdots\mu_J}\text{ for }\vec{e}\text{ transverse}$$

$$\sim -g_{\mu_1 j}(m_{A_1}/2\omega)(\vec{\epsilon}\times\vec{k})_j K_{\mu_2}\cdots K_{\mu_2}\psi^{\mu_1\cdots\mu_J}\text{ for }\vec{e}\text{ longitudinal}. \tag{8}$$

We see that for either parity exchange the A_1 is produced with transverse polarization.[11]

A number of experimental consequences follow from the assumption of strong A_1 photoproduction.

(i) The use of a plane-polarized photon beam can discriminate between abnormal- and normal-parity exchange since the polarization state e of the A_1 is measured in its decay $A_1 \to \rho + \pi$. This is clear from Eqs. (7) and (8) which predict a transverse $\vec{e}$ parallel or perpendicular to the photon $\vec{\epsilon}$, respectively, in these two cases.

(ii) If vector exchange turns out to be important, coherent photoproduction of A_1^0's on nuclear targets should occur with

$$\sigma_{\text{tot}}(\gamma + [N,Z] \to A_1^{\;0} + [N,Z]) \sim (N\pm Z)^2 s^{2\alpha_V(0)-1},$$

where the ambiguous sign is (+, −) for (isoscalar, isovector) exchange and $\alpha_V(0) < 1$.

(iii) If axial exchange turns out to be important, the energy variation will yield first information on the intercept $\alpha_A(0)$ of this trajectory.

(iv) The difference between π^+ and π^- production at angles $\theta < \theta_p$ is a measure of charged A_1 production since the forward pion yield from neutral mesons must necessarily be the same for $\pi^{\pm}$.

(v) In experiments which observe more than one charged particle, the presence of $\pi^+\pi^+$ ($\pi^-\pi^-$) can serve as a signature of $A_1^{\;+}$ ($A_1^{\;-}$) production.

The above conclusions can also be extended to the photoproduction of bosons with $J = 2$. Conclusions analogous to those obtained above for pions from ρ^0 and A_1 production apply to those from f^0 and A_2 production which have the same predominant decay chains, respectively.

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ful conversations and for communicating the results of work in which he has been engaged which overlaps some of the conclusions presented here. We also understand that M. L. Ter-Mikaelyan has expressed similar conclusions with respect to the importance of A_1 photoproduction leading to pions at $\theta < \theta_p$.

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[1]R. B. Blumenthal et al., Phys. Rev. Letters 11, 496 (1963).

[2]S. D. Drell, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 8-12 June 1965 (Springer Verlag, Berlin, 1965), Vol. I, p. 71.

[3]A. Barna et al., Phys. Rev. Letters 18, 360 (1967); A. Boyarski et al., ibid. 18, 363 (1967); S. M. Flatté et al., ibid. 18, 366 (1967).

[4]A detailed report of our work is being prepared for publication elsewhere.

[5]A possible exception for extreme kinematic conditions is discussed in Ref. 9.

[6]Momentum factors of $k-q$ could be used in place of $k+q$ in Eq. (1). However, such terms only couple via the spin-$<J$ components that are present when the spin-J particle is off mass shell. For the dominant contribution as $s\rightarrow\infty$ these terms are not important.

[7]The single exception to our conclusion is the possibility of a conspiracy between trajectories at $t=0$. We will report on this elsewhere. See also the discussions of conspiracy in photopion production by M. B. Halpern, to be published, and P. K. Mitter, to be published.

[8]L. J. Lanzerotti et al., Phys. Rev. Letters 15, 210 (1965); Cambridge Bubble Chamber Group, Phys. Rev. 146, 994 (1966); R. Erbe et al. (Aachen-Berlin-Bonn-Hamburg-Heidelberg- München Collaboration), Nuovo Cimento 48A, 262 (1967); S. Ting, private communication.

[9]In the extreme kinematic limit in which the observed pion from rho decay has more than ≈90% of the incident photon energy, the dip can be absent. However, to avoid the dip one must require that the rho mesons produced at nonforward angles have a polarization state that differs substantially from the "naive" diffraction-model prediction of transverse rho polarization with respect to the incident photon direction as seen in the rho rest frame. The "naive" model seems to be incorrect at photon energies up to 6 BeV (Ref. 8) but it is an open question as to what will happen at higher energies. See the detailed calculations of Y. S. Tsai, Stanford Linear Accelerator Center User's Handbook, 1966 (unpublished). We thank Dr. Tsai and Dr. Yennie for a discussion on this point.

[10]The convection current coupling which effectively extends V_2 to $J=1$ can be seen to be unimportant by an argument similar to the case of pion exchange.

[11]It is clear that the same conclusion holds for 1^- meson production.

KINEMATIC INTERPRETATION OF THE LOW-MASS $K\pi\pi$ ENHANCEMENT IN $Kp\pi\pi$ FINAL STATES*

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An outstanding feature of K^-p and K^+p interactions[1-8] above 4 BeV/c is a pronounced $K\pi\pi$ mass enhancement, extending from ~1200 to ~1500 MeV, consisting[9] of $K^*+\pi$ and some $K+\rho$. The enhancement is produced only when the $K\pi\pi$ system recoils against a proton—not when it recoils against a neutron.[1-3] These characteristics have been interpreted by several groups as being due to resonance production[7,10] superimposed on a Deck-effect background.[11] We present here semiquantitative evidence that one may interpret the $K\pi\pi$ enhancement in the final state $p\bar{K}^0\pi^0\pi^-$ at 4.6 and 5.0 BeV/c as being due to the operation of four meson-exchange processes, all characterized by elastic scattering at the bottom vertex, and thus leading to Deck-effect peaking in $M(K\pi\pi)$. In addition to the usual diagram [Fig. 1(a)], we