Possible Charge-Conjugation Noninvariance in the Photoproduction of Neutral ρ Mesons

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We examine theoretically the dominant features of the experimental data on the reaction $\gamma+p\rightarrow\rho^0+p$ which have recently been presented by the Cambridge Electron Accelerator bubble-chamber collaboration. In accord with the experimentalists' conclusions, we find that (a) the exchange of a single π^0 does not seem to play an important role in the production mechanism, perhaps merely because of a relatively small value for the $\rho^0\pi^0\gamma$ vertex; (b) a diffraction production mechanism may play a significant role in the production of ρ^0 at near-forward angles. However, for photon laboratory energies between 1.8 and 6 BeV, about 40% of the ρ^0 are produced at center-of-mass angles θ with $\cos\theta<0.85$. We address ourselves to the question of whether the exchange of a neutral vector meson, in particular the ω^0, can be playing a significant role in the production mechanism; perhaps a dominant role for ρ^0 produced at other than near forward angles. The $\rho^0\omega^0\gamma$ vertex violates charge-conjugation invariance and time-reversal invariance. We find that the present data on (1) the forward differential cross section as a function of photon energy, (2) the production angular distribution and total cross section at about 5 BeV, and (3) the behavior of the ρ^0 density matrix elements as functions of production angle and photon energy, are completely consistent with the results from the exchange of an ω^0, with a C-violating transition magnetic moment at the $\rho^0\omega^0\gamma$ vertex of the order of unity, in units of $e\hbar/2m_\rho$. It appears that further experiments to elucidate the behavior of the density matrix elements as functions of production angle, in particular at the larger production angles, could detect a variation that is possibly characteristic of the ω^0-exchange mechanism. When our results correspond to some aspect of the data which can also be correlated with diffraction production, we say only that the data are consistent with C noninvariance. When our results give rise to some striking aspect which is not an evident feature of diffraction production, we say only that that C noninvariance provides one possible interpretation should the data exhibit this aspect. In the Appendix, we note a model in which C noninvariance in the electromagnetic interaction of neutral vector mesons manifests itself in certain processes through C noninvariant and isotopic-spin-violating vertices among hadrones, which are of order α.

I. INTRODUCTION

EXTENSIVE experimental data on the reaction $\gamma+p\rightarrow\rho^0+p$ have recently been presented by the Cambridge Electron Accelerator (CEA) bubble-chamber collaboration.[1] In this paper, we examine theoretically the dominant features of these data with the aim of determining whether the exchange of a neutral vector meson, the ω^0, can be playing a significant role in the production mechanism. In order for this to be possible, there must exist a charge-conjugation (C) noninvariant $\rho^0\omega^0\gamma$ vertex. With the assumption of CPT invariance and parity (P) conservation, this vertex also violates time-reversal invariance (T). The hypothesis has been put forth[2,3] that the electromagnetic interaction violates CP and T invariances. The hypothesis is consistent with existing experiments[3] and provides one possible interpretation of (a) the experimental discovery[4–6] of $K_L{}^0\rightarrow 2\pi$, which shows that CP fails in a weak interaction, and (b) the experimental discovery[7–9a] of an energy asymmetry between the π^+ and π^- emerging from the decay $\eta\rightarrow\pi^++\pi^-+\pi^0$, which shows that C fails in an interaction far stronger than the weak interaction.[10] Further evidence bearing on the hypothesis would be supplied by the existence or nonexistence of vertices involving a photon and two neutral vector mesons, which could lead to the following decays[3]:

$$\omega^0\rightarrow\rho^0+\gamma\,, \tag{1a}$$

$$\phi^0\rightarrow\rho^0+\gamma\,, \tag{1b}$$

$$\phi^0\rightarrow\omega^0+\gamma\,. \tag{1c}$$

However, with a transition magnetic moment of about one unit of $e\hbar/2m_\rho$ (m_ρ is the ρ^0 mass$=0.75$ BeV), the rate for process (1a) is only about 10^{-5} of the ω^0 total decay rate. The branching ratios for reactions (1b) and (1c) are also relatively small[3] ($\approx 10^{-2}$) and difficult to measure.[11] Thus we argue the need to study the

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photoproduction of neutral vector mesons for evidence pertaining to the existence of such C,T-noninvariant vertices.

In Sec. II, we briefly summarize and comment upon the dominant features of two production mechanisms within the framework of C invariance that have recently been discussed.[1,12–14] In Sec. III, we perform the calculations and present the results for the exchange of an ω^0. These results are given for the case of no final-state absorption corrections, and for the unphysical, but illustrative case in which the S wave, alone, has been completely removed from the final state. In Sec. IV, we consider certain qualitative features of some production mechanisms involving baryon exchange in the s and u channels. In Sec. V we discuss our conclusions that the dominant features of the present data are consistent with a significant role for the C-noninvariant production mechanism. We remark upon an especially curious feature of the experimental data, from the point of view of the ω^0-exchange model. We emphasize how experiments might further probe this matter, in particular by studying the ρ^0 density matrix elements as functions of production angle at the larger production angles. In the Appendix we remark upon a model in which the neutral vector mesons play an essential role in electromagnetic C noninvariance, and in which a significant $\pi^+-\pi^-$ asymmetry in $\eta\to\pi^+ +\pi^-+\pi^0$ might be understood without the expectation that the branching ratio $(\eta\to\pi^0+e^++e^-)/(\eta\to 2\gamma)$ be much greater than of order α^2.

II. π^0 EXCHANGE AND DIFFRACTION PRODUCTION

The experimentalists[1] have stated that the production mechanism involving the exchange of a single π^0 strongly disagrees with several aspects of the data. Perhaps most strikingly, the theoretical production cross section at 0° in the center-of-mass system $(d\sigma/d\Omega)(0°)$ falls at high energies like s^{-2}, where s is the square of the total center-of-mass (c.m.) energy. This fall is evident above 2-BeV photon laboratory energy and persists when strong final-state absorption corrections are made to the theory; such a fall is not a feature of the data. Independently of the behavior of the forward production cross section, the $\pi^+-\pi^-$ relative momentum in the rest system of the decaying ρ^0 should be correlated with the beam direction, as seen in the ρ^0 rest system, according to $\sin^2\bar{\theta}$ ($\bar{\theta}$ is the Gottfried-Jackson angle, in the notation of Ref. 1), for ρ^0 produced at *any* c.m. production angle θ. This result is not grossly modified[1] by strong final-state absorption corrections; the experimental data fail to show this feature, especially for ρ^0 produced at θ other than almost exactly 0°. For a decay width $\Gamma(\rho^0\to\pi^0+\gamma)\approx 0.1$ MeV the π^0-exchange mechanism gives only a $(d\sigma/d\Omega)(90°)\lesssim 1$ μb/sr. This decay width may be much smaller than 0.1 MeV. It has been noted[1] that its smallness is consistent with the hypothetical A-selection rule,[15] which in turn can be used to correlate the extreme depression of the rate for $\eta\to\pi^++\pi^-+\gamma$ relative to that for $\eta\to\pi^++\pi^-+\pi^0$.[15] The former decay may proceed virtually through $\eta\to\rho^0+\gamma$, which is depressed comparably to $\rho^0\to\pi^0+\gamma$.

For ρ^0 production at near-forward angles one may consider a diffraction production mechanism.[1,12,13] Let us remark immediately that we believe that such a mechanism arises from general considerations independent of the specific models used in the calculations,[12,13] and therefore is likely to play some role in accounting for the pronounced forward peaking that is surely the dominant and most unambiguous feature of ρ^0 photoproduction at high energies. However, if the pure diffraction production differential cross section falls off[1,13] (from a value at 0° of the order of a few tens of microbarns per steradian[1]) like e^{At}, where $A\cong 10$ $(\mathrm{BeV}/c)^{-2}$ and t is the four-momentum transfer between the initial and final protons, then it is not clear that this mechanism can reasonably be called upon to correlate the features of ρ^0 produced at, say, $\cos\theta<0.9$, for photons at 5 BeV in the laboratory $[t<-0.4(\mathrm{BeV}/c)^2]$. There are two features of this mechanism, aside from the pronounced forward peak, that are in reasonable accord with the data. (1) The energy dependence of the forward production cross section is expected to be given by[1]

$$(d\sigma/d\Omega)(0°)\propto kp\,, \tag{2}$$

where k and p are the photon and ρ^0 c.m. momenta, respectively. We shall show in Sec. III that this energy dependence is also precisely what is to be expected from the exchange of an ω^0. (2) The ρ^0 helicity is expected to be that of the photon, ± 1; this is an exact statement only at 0°.[1] Accordingly, the $\pi^+-\pi^-$ relative momentum in the ρ^0 rest system should be approximately correlated with the unit vector $\hat{k}$, *or* the unit vector $\hat{p}$, according to $\sin^2\alpha$ (where α is the Adair angle, in the notation of Ref. 1). One can ask what the decay distribution in $\bar{\theta}$ will look like for events that are *assumed* to satisfy the $\sin^2\alpha$ Adair distribution. A bit of geometry gives the result

$$W(\bar{\theta})\propto\frac{1}{2\pi}\int_0^{2\pi}d\phi\,\sin^2\alpha =1-\cos^2\bar{\theta}\cos^2y-\tfrac{1}{2}\sin^2\bar{\theta}\sin^2y\,, \tag{3}$$

where ϕ is the Treiman-Yang angle[1] and $y=\psi-\theta$, and where, with v the ρ^0 center-of-mass velocity,

$$\sin\psi=m_\rho v\sin\theta/k(1-v\cos\theta)\,. \tag{4}$$

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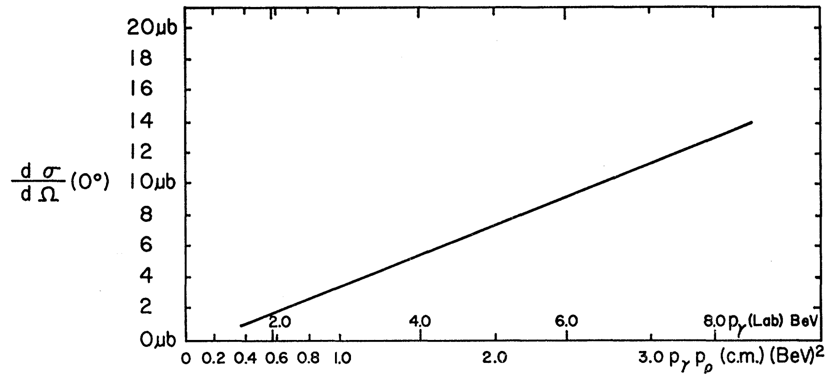
FIG. 1. The c.m. forward differential cross section for $\gamma+p\rightarrow\rho^0+p$ via the ω^0-exchange mechanism, as a function of energy. The abscissa is in BeV and $(\mathrm{BeV})^2$; the ordinate is in μb/sr. The parameter b is taken$=1$, corresponding to a transition magnetic moment of $e\hbar/2m_p$.



We see from Eq. (4) that for $k\gg1$ and $v\rightarrow\approx1$, the angles ψ and y may be very different from zero, even for production angles θ sufficiently close to zero for applicability of the diffraction mechanism. This results in a kinematic tendency for $W(\bar{\theta})$ to go from $\sin^2\bar{\theta}\rightarrow$ isotropy$\rightarrow\lambda\cos^2\bar{\theta}+\sin^2\bar{\theta}$ with $\lambda\leq2$, as θ increases at fixed v (or as v increases at fixed θ). We shall show in Sec. III that the ω^0-exchange mechanism leads to rapidly varying ρ^0 density matrix elements as a function of θ, such that $W(\bar{\theta})$ is expected to go from $\sin^2\bar{\theta}\rightarrow$ isotropy$\rightarrow\approx\cos^2\bar{\theta}$ as θ ranges over its full interval from 0 to π, only a small fraction of which is contributed to significantly by diffraction production.

III. *C* NONINVARIANCE

We first give the calculation without modification for final-state absorption effects. We also approximate all vertex form factors by constants. The ω^0pp vertex is given by

$$(4\pi)^{1/2}\bar{u}(p_2)\{F_1\gamma_\alpha+F_2\sigma_{\alpha\beta}(p_1-p_2)_\beta\}u(p_1)$$
$$=(4\pi)^{1/2}\bar{u}(p_2)\{f_1\gamma_\alpha+f_2(p_2+p_1)_\alpha\}u(p_1)\,,\quad(5)$$

with

$$f_1=F_1+2mF_2\approx0.61\,,$$
$$f_2=-F_2\approx0.09/2m\,,$$
$$F_1^2\approx G_{\rho\pi\pi}^2/4=0.5\,,$$
$$F_2/F_1\approx(\mu_p+\mu_n)/2m=-0.13/2m\,.$$

In Eqs. (5), m is the nucleon mass, $(p_1)_\alpha$ and $(p_2)_\alpha$ are the initial and final proton four-momenta, respectively, $u(p_1)$ and $\bar{u}(p_2)$ are initial and final Dirac spinors, $G_{\rho\pi\pi}^2$ is estimated from the ρ-meson width, μ_p and μ_n are the anomalous magnetic moments of proton and neutron, respectively; and we have used the electromagnetic isoscalar form-factor data, assumed to be described entirely by the ω^0, in estimating F_1 and F_2.[15a] The general C-noninvariant $\rho^0\omega^0\gamma$ vertex is given by[3]

$$\langle\nu,\rho^0|j_\lambda|\omega^0,\mu\rangle=i(4\pi\alpha)^{1/2}\{(2p-k)_\lambda(\mathfrak{F}_1\delta_{\mu\nu}+\mathfrak{F}_2k_\mu k_\nu)$$
$$+\mathfrak{F}_3\delta_{\lambda\nu}k_\mu+\mathfrak{F}_4\delta_{\lambda\mu}k_\nu+k_\lambda(\mathfrak{F}_5\delta_{\mu\nu}+\mathfrak{F}_6k_\mu k_\nu)\}\,,\quad(6)$$

[15a] Estimates from nucleon-nucleon scattering suggest that F_1 may be significantly larger than this estimate. This would result in a corresponding reduction in our estimate for the C-violating parameter, b.

where p_λ and k_λ are the ρ^0 and photon four-momenta, respectively, and $\mathfrak{F}_1=0$ at $k_\mu^2=0$. The vertex for $\rho^0\rightarrow\pi^++\pi^-$ is given by

$$(4\pi)^{1/2}GQ_\lambda\,,\quad(7)$$

where $G=G_{\rho\pi\pi}$, and $Q_\lambda=(p_+-p_-)_\lambda$ with $(p_+)_\lambda$ and $(p_-)_\lambda$ the π^+ and π^- four-momenta, respectively. The matrix element computed by using Eqs. (5)–(7) is then

$$M=\frac{i(4\pi)^{3/2}\alpha^{1/2}G(m^2/4k\omega E_1E_2)^{1/2}}{(t-m_\omega^2)}\bar{u}(p_2)$$
$$\times\{(\mathfrak{F}_2 2e\cdot pQ\cdot k+\mathfrak{F}_3e\cdot Q)[f_1\gamma\cdot k+f_2(p_1+p_2)\cdot k]$$
$$+\mathfrak{F}_4[f_1\gamma\cdot e+f_2(p_1+p_2)\cdot e]Q\cdot k\}u(p_1)\,.\quad(8)$$

In Eq. (8), ω, E_1, and E_2 are the c.m. energies of ρ^0, initial proton, and final proton, respectively, e_λ is the photon polarization four-vector, and m_ω is the ω^0 mass$=0.78$ BeV. Gauge invariance allows one to write the remaining three form factors in terms of two[3]:

$$\mathfrak{F}_2=a\,,$$
$$\mathfrak{F}_3=(m_\omega^2-m_\rho^2)\tfrac{1}{2}a-b\,,$$
$$\mathfrak{F}_4=(m_\omega^2-m_\rho^2)\tfrac{1}{2}a+b\,,\quad(9)$$

where a and b are related to the transition magnetic moment μ, and quadrupole moment q, by $\mu=be/2\bar{m}$ and $q=(b-2\bar{m}^2a)e^2/\bar{m}^2$ as $m_\omega\rightarrow m_\rho\rightarrow\bar{m}$. We are going to work with the hypothesis that the terms in a can be neglected. For the terms in $\mathfrak{F}_3$ and $\mathfrak{F}_4$, we are assuming that the $\omega^0-\rho^0$ mass difference is small enough to justify this neglect. For the term in $\mathfrak{F}_2$ in Eq. (8), we note[12] that the factor $p\cdot e=-\mathbf{p}\cdot\mathbf{e}\propto\sin\theta$; thus if a were dominant we might expect some structure around $\theta=\frac{1}{2}\pi$ in the production angular distributions; this is not a feature of the data. When our results correspond to some aspect of the data which can also be correlated by diffraction production, we say only that the data are consistent with C noninvariance with b dominant. When our results give rise to some striking aspect which is not an evident feature of diffraction production, we say only that C noninvariance with b dominant provides *one* possible interpretation, should the data exhibit this aspect.

The general expression for the ρ^0 decay distribution, as a function of the angles $\bar{\theta}$ and ϕ, is given in terms of the density matrix elements ρ_{ij} by

$$W(\bar{\theta},\phi)=(3/4\pi)\{\rho_{00}\cos^2\bar{\theta}+\rho_{11}\sin^2\bar{\theta} -\rho_{1,-1}\sin^2\bar{\theta}\cos 2\phi-\sqrt{2}(\mathrm{Re}\rho_{10})\sin 2\bar{\theta}\cos\phi\}. \quad (10)$$

The c.m. production differential cross section is then

$$(d\sigma/d\Omega)(k,\theta)=\rho_{00}+2\rho_{11}. \quad (11)$$

From the matrix element in Eq. (8) we obtain, with $x=\cos\theta$,

$$\rho_{11}=N[m_\rho^2-m_\omega^2-2k\omega(1-vx)]^{-2}\{f_1^2 2k^2\omega s^{1/2}(E_2/\omega+vx)+2mf_1f_2(k\omega)^2(2s^{1/2}/\omega-1+vx)^2 +f_2^2(2m^2-\tfrac{1}{2}m_\rho^2+k\omega(1-vx))(k\omega)^2(2s^{1/2}/\omega-1+vx)^2\}, \quad (12a)$$

$$\rho_{00}=N[m_\rho^2-m_\omega^2-2k\omega(1-vx)]^{-2}(k\omega(1-vx)/m_\rho)^2\{f_1^2[2k\omega(1-vx)-m_\rho^2+2s(v^2(1-x^2)/(1-vx)^2)] +2mf_1f_2(4s)(v^2(1-x^2)/(1-vx)^2)+f_2^2[(4m^2-m_\rho^2+2k\omega(1-vx))(2s)(v^2(1-x^2)/(1-vx)^2)]\}, \quad (12b)$$

$$-\sqrt{2}\,\mathrm{Re}\rho_{10}=N[m_\rho^2-m_\omega^2-2k\omega(1-vx)]^{-2}(k\omega)^2(s^{1/2}/m_\rho)v(2s^{1/2}/\omega-1+vx) \times(1-x^2)^{1/2}\{f_1^2+4mf_1f_2+f_2^2[4m^2-m_\rho^2+2k\omega(1-vx)]\}, \quad (12c)$$

$$\rho_{1,-1}=0, \quad (12d)$$

with $N=(\tfrac{1}{4}\alpha|b|^2)(p/ks)$.

We neglect terms in f_2^2 ($f_2\sim 0.1/2m$) and enumerate certain striking features of Eqs. (12a)–(12d). (1) The elements ρ_{11} and ρ_{00} are very strong functions of x. At $x=1$, $\rho_{00}\propto|t|$ and hence is essentially zero at high energies, whereas ρ_{11} increases rapidly near $x=1$ and gives rise to a forward differential cross section which goes asymptotically as

$$(d\sigma/d\Omega)(0°)\approx(\alpha|b|^2/4m_\omega^4)(2f_1^2+8mf_1f_2)(kp). \quad (13)$$

This is identical with the energy dependence of the diffraction production mechanism. In Fig. 1 we exhibit the exact forward production cross section as a function of energy, with $b=1$. (2) For ρ^0 produced at 0°,

$$W(\bar{\theta})=\int_0^{2\pi}d\phi\,W(\bar{\theta},\phi)=\tfrac{3}{2}\sin^2\bar{\theta}(=\tfrac{3}{2}\sin^2\alpha).$$

This $\sin^2\bar{\theta}$ decay distribution changes rapidly toward isotropy and then toward $\cos^2\bar{\theta}$ for $x<0.85$. This is illustrated in Figs. 2 and 3. In Fig. 2 we show the integrated $W(\bar{\theta})$ for all ρ^0 produced with $-1\leq x\leq 0.85$, at a photon laboratory energy of 2 BeV. We note also that the ratio $r=\rho_{00}/\rho_{11}\propto|t|$ asymptotically, and approaches this limit nonmonotonically from above. Thus, at a fixed t, there is a smaller admixture of $\cos^2\bar{\theta}$ in the decay distribution at 10 BeV (where the asymptotic limit is being approached) than at 5 BeV, but the r are comparable at 5 BeV and 2 BeV. (3) The element $\rho_{1,-1}$ vanishes and thus $W(\phi)=\int_{-1}^{1}d(\cos\bar{\theta})W(\bar{\theta},\phi)$ is isotropic. (4) However, the quantities $\tilde{W}(\phi)=\int_{-1(0)}^{0(1)}d(\cos\bar{\theta})W(\bar{\theta},\phi)$ are not isotropic, since $\mathrm{Re}\rho_{10}$ does not vanish except at $x=\pm 1$, (where, of course, it must, as ϕ loses its significance as an angle between two defined planes). In Fig. 4 we show $\int_0^1 d(\cos\bar{\theta})W(\bar{\theta},\phi)$ for all ρ^0 produced with $-1\leq x\leq 0.85$, at a photon laboratory energy of 5 BeV.

In Figs. 5–7 we give the production angular distributions at photon laboratory energies of 2, 5, and 10 BeV, respectively. With $b\cong 1$, the total cross sections are about 4, 10.4, and 15 μb, respectively. With neglect of f_2^2 and also a, but *before* form-factor corrections and corrections due to absorption in the final state are made, the total cross section from the exchange of a vector meson does *not* grow drastically with energy—the increase is asymptotically logarithmic and comes from the ρ_{00} term in Eq. (11).

Consider the differential cross section in Fig. 6 for 5-BeV photons. About 60% of the cross section is at $-1\leq x\leq 0.85$. The forward cross section is $(d\sigma/d\Omega)(0°)\cong 7$ μb/sr. The experimental forward cross section at this energy is roughly 45 μb/sr.[1] From this we can estimate the forward diffraction production amplitude, which is approximately coherent with the ω^0-exchange amplitude. Assuming the $e^{At/2}$ dependence for the diffraction amplitude, we obtain a cross section of ≈ 11.2 μb from $1\geq x\geq 0.85$, from the diffraction and

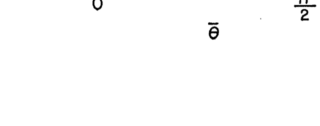


FIG. 2. The decay distribution $W(\bar{\theta})=\int_0^{2\pi}d\phi W(\bar{\theta},\phi)$ from Eq. (10), where $\bar{\theta}$ is the angle between the $\pi^+-\pi^-$ relative momentum in the ρ^0 rest system, and the photon-beam direction as seen in the ρ^0 rest system. The photon laboratory energy is 2 BeV and only ρ^0 produced with $x\leq 0.85$ are included. The abscissa represents $\bar{\theta}$ and the distribution is symmetric about $\bar{\theta}=\tfrac{1}{2}\pi$.

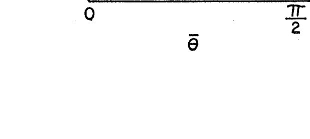


FIG. 3. The same distribution as in Fig. 2, but at a photon laboratory energy of 5 BeV.

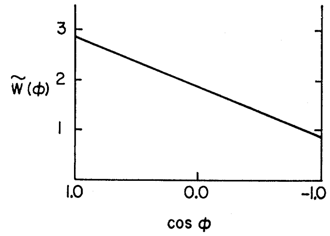


FIG. 4. The decay distribution $\tilde{W}(\phi)=\int_0^1 d(\cos\bar{\theta})\times W(\bar{\theta},\phi)$, where ϕ is the Treiman-Yang angle. The photon laboratory energy is 5 BeV and only ρ^0 with $x\leq 0.85$ are included. The abscissa represents $\cos\phi$.

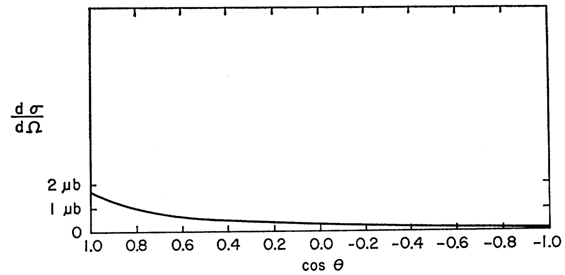


FIG. 5. The c.m. differential cross section for $\gamma+p\rightarrow\rho^0+p$ via the ω^0-exchange mechanism, at 2 BeV photon laboratory energy. The abscissa is $x=\cos\theta$. The ordinate is in μb/sr. The parameter b is taken $=1$, corresponding to a transition magnetic moment of $e\hbar/2m_\rho$.

ω_0-exchange amplitudes. From $-1\leq x\leq 0.85$ we obtain a cross section of about 6.2 μb, from the ω^0-exchange amplitude. The total cross section of about 17 μb does not disagree with the data[1] and the percentage of the total cross section from $-1\leq x\leq 0.85$ is now $\sim$36%, also not in disagreement with the data.

We turn now to the matter of whether the above results are grossly modified by absorption effects in the final state.[16,17] Considering the tentative nature of the hypothesis of C noninvariance, and the uncertainties in the present knowledge of ρ^0-proton scattering, we have done a calculation meant to be illustrative of these effects, rather than a comprehensive inclusion of them. To this end we have completely removed from the matrix element of Eq. (8) the amplitudes for the two final S states corresponding to total angular momenta $\frac{1}{2}$ and $\frac{3}{2}$, through use of the projection operators

$$P_{1/2}=\hat{\epsilon}\cdot\hat{e}+i\boldsymbol{\sigma}\cdot\hat{\epsilon}\times\hat{e},$$
$$P_{3/2}=2\hat{\epsilon}\cdot\hat{e}-i\boldsymbol{\sigma}\cdot\hat{\epsilon}\times\hat{e}, \qquad (14)$$

where $\hat{e}$ is a unit polarization vector for the photon in the laboratory, $\hat{\epsilon}$ is a unit polarization vector for the ρ^0 in its rest system, and $\boldsymbol{\sigma}$ represents the Pauli spin operators. We have computed the corrections to all of the density matrix elements in Eqs. (12a)–(12d) and we note the following features. (1) The strong dependence of ρ_{11} and ρ_{00} on production angle persists, but the decay distributions at 5 BeV change somewhat more slowly as a function of x, from $\sin^2\bar{\theta}$ toward distributions that are largely isotropic. (2) The element $\rho_{1,-1}$ is nonzero and negative for $x\neq\pm1$. However $|\rho_{1,-1}|$ is two to ten times smaller than either ρ_{00} or ρ_{11} for $x<-0.2$, leading to the expectation that $W(\phi)$ remains essentially isotropic for backward produced ρ^0 from this production mechanism alone. (3) The distribution $\tilde{W}(\phi)$ in Fig. 4 is slightly altered by the presence of a term in $\cos 2\phi$; aside from this the slope steepens by a factor of about two. (4) The production angular distribution in Fig. 6 is altered. The forward-peaking effect is "narrowed" by relative depression of $d\sigma/d\Omega$ between $x=0.9$ and $x=0.6$. The total cross section is reduced to about 5.6 μb.

These results suggest that in further experiments one might attempt to discern the characteristic variations with x of ρ_{11} and ρ_{00} outside of the dominant forward peak, as exemplified by Figs. 2 and 3. In addition, it might be possible to test the characteristic $\tilde{W}(\phi)$ distribution in Fig. 4, again for ρ^0 produced outside of the forward peak.[18] The large difficulty with these suggestions is that the differential cross sections outside of the forward peak are relatively small, <1 μb/sr. Studies of these small cross sections are experimentally difficult, and, on the theoretical side, other small contributions to the production mechanism may distort the features of the ω^0 exchange. We examine briefly in Sec. IV some aspects of baryon exchange.

IV. BARYON EXCHANGE

Experiment indicates[1] that there is a tendency for the decay distribution with respect to $\hat{k}$ to persist as $\approx\sin^2\alpha$ for ρ^0 produced at other than $\theta\cong 0°$. This might suggest a production mechanism that falls off less rapidly than e^{At}, but which has the feature in common with diffraction of $\sin^2\alpha$ decay for $\theta=0°$. It is then possible for this distribution to persist approximately at relatively small θ, even at θ (and k) such as $e^{-A|t|}\ll 1$. To investigate this point, we exhibit in Table I the decay distributions $W(\cos\alpha)$ to be expected for ρ^0 produced at $\theta=0°$ via various baryon exchanges in the direct (or s) channel, together with the production angular distribution expected from each particular exchange. We see that only case (b) [and approximately, (e)] gives a $W(\cos\alpha)=\sin^2\alpha$ at 0° together with an isotropic production angular distribution. Even this

[16] N. Sopkovitch, Nuovo Cimento **26**, 186 (1962).

[17] K. Gottfried and J. D. Jackson, Nuovo Cimento **34**, 735 (1964).

[18] $\tilde{W}(\phi)$ in Fig. 4 is approximately given by $2+0.9\cos\phi$. The ratio R, of the number of events with $\frac{1}{2}\pi\leq\phi\leq\pi$ to those with $0\leq\phi\leq\frac{1}{2}\pi$ is then $\sim$0.55. Professor B. Feld has kindly sent us two experimental distributions, one the $\tilde{W}(\phi)$ for ρ^0 events at *all* production angles which decay with $0\leq\bar{\theta}\leq\frac{1}{2}\pi$; and a second the $\tilde{W}(\phi)$ for ρ^0 events at all production angles which decay with $\frac{1}{2}\pi\leq\bar{\theta}\leq\pi$. (Note that Fig. 4 contains only events with production $x\leq 0.85$). In the first distribution there are 205 events with $\frac{1}{2}\pi\leq\phi\leq\pi$ and 253 events with $0\leq\phi\leq\frac{1}{2}\pi$. If we simply *assume* that this distribution contains an isotropic (in ϕ) background of about 60% of the events, from ρ^0-production angles with $x\geq 0.85$, the ratio R is $\sim$0.58. However, the second experimental distribution is perfectly isotropic, with 265 events with $\frac{1}{2}\pi\leq\phi\leq\pi$, and 262 events with $0\leq\phi\leq\frac{1}{2}\pi$. The fact that the total number of events in the two distributions differ, and that the two are not simply reflections of one another through $\phi=\frac{1}{2}\pi$, prevents the drawing of any conclusions from these data alone.

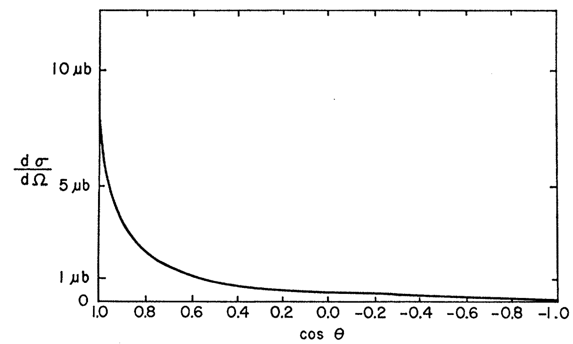


FIG. 6. The same distribution as in Fig. 5, but at a photon laboratory energy of 5 BeV.

reasonable case (nucleon exchange) requires the dynamical circumstance that the ρ^0 spin and angular momentum couple to 1 and not appreciably to 0. There is the further general objection that one might then expect the crossed-channel process (nucleon exchange in the u channel) to give a backward peak to ρ^0 production. Experiment can check on whether a process such as (b) is happening, independently of the matter of the expected backward peak, which might be somehow suppressed. That is, ρ^0 produced in a small interval $\Delta\theta$ about $\theta=\pi$ should show a $\sin^2\alpha$ decay distribution with respect to $\hat{k}$, and also a $\sin^2\bar{\theta}$ decay distribution with respect to the beam direction as seen in the ρ^0 rest system, since this direction remains very close to $\hat{k}$ for $\theta\approx\pi$, *even* at high energies and $v\to\approx 1$. This is distinctly different from the $\approx\cos^2\bar{\theta}$ decay distribution expected from ω^0 exchange.

V. CONCLUSION

In Sec. IV we noted a curious feature of the experimental data, namely, that the ρ^0 decay distribution with respect to $\hat{k}$ tends to continue to have an important $\sin^2\alpha$ component for ρ^0 produced at other than $\cong 0°$. We quote the experimentalists[1] on this point: "our data favor a theory in which the distribution would tend to remain $\sin^2\alpha$, even for production angles well off zero degrees." Now it is well known that α is *not* the "natural" angle for studying the decay distribution for the ω^0-exchange mechanism (in the t channel). Nevertheless, let us assume that this mechanism operates and produces a decay distribution $W(\bar{\theta},\phi)$ in the "natural" angles $\bar{\theta}$ and ϕ, which changes from $\sin^2\bar{\theta}\to\approx\cos^2\bar{\theta}$ from $x=1$ to $x\lesssim 0.5$ (we neglect Reρ_{10}, since our argument is meant to be qualitative). For events at a given x, we can ask what $W(\alpha)$ qualitatively looks like. We find

$$W(\bar{\theta})=\sin^2\bar{\theta}\to W(\alpha)=1-\cos^2\alpha\cos^2y-\tfrac{1}{2}\sin^2\alpha\sin^2y$$
$$=\sin^2\alpha \quad \text{for} \quad y=0,\pi$$
$$=\cos^2\alpha+\tfrac{1}{2}\sin^2\alpha \quad \text{for} \quad y=\tfrac{1}{2}\pi, \tag{15a}$$

$$W(\bar{\theta})=\cos^2\bar{\theta}\to W(\alpha)=\cos^2\alpha\cos^2y+\tfrac{1}{2}\sin^2\alpha\sin^2y$$
$$=\cos^2\alpha \quad \text{for } y=0,\pi$$
$$=\tfrac{1}{2}\sin^2\alpha \quad \text{for} \quad y=\tfrac{1}{2}\pi. \tag{15b}$$

The angle y is defined before Eq. (4); it is 0° at $x=\pm 1$ and reaches a maximum value $<\pi$ at $x=1-(1-v^2)^{1/2}$. For 5-BeV photons, this maximum value is 74° at a ρ^0-production angle, $\theta\cong 59°$. From Eq. (15b), we observe that ρ^0 produced at these large angles, with density matrix elements such that $W(\bar{\theta},\phi)\approx\cos^2\bar{\theta}$, will have $W(\alpha)\approx\sin^2\alpha$.

We are well aware that in a matter as critical as the charge-conjugation invariance of the electromagnetic interaction one will not be able to draw a final conclusion from the analysis of a process as rich in potential structure (and incomputable, in detail) as $\gamma+p\to\rho^0+p$. Experiments that are definitive tests of the symmetry principles have been performed[7–9a] and others[19] are under way in order to test electromagnetism, specifically. Nevertheless, should the symmetry principles C and T fail in electromagnetism, the possible extreme depression of the C-invariant π^0-exchange mechanism in ρ^0 photoproduction opens the way to an attempt to probe the C-noninvariant vertex between a photon and two neutral vector mesons, which may give rise to the

TABLE I. This table gives the decay distributions $W(\cos\alpha)$ for ρ^0 produced at $x=1$ (and also at $x=-1$), and the c.m. production angular distribution $(d\sigma/d\Lambda)(x)$ to be expected from the exchange of various baryons of spin-parity J^P in the s channel. The electromagnetic multipole involved in each transition is also listed, as is l, the final-state orbital angular momentum of the ρ^0-proton system, and j, the angular momentum to which l and the ρ^0 spin couple. The angle α is the Adair angle between the $\pi^+-\pi^-$ relative momentum in the ρ^0 rest system and the photon-beam direction in the laboratory.

	J^P	Exchanged baryon	Multipole	l	j	$W(\cos\alpha)$	$(d\sigma/d\Omega)(x)$
(a)	$\frac{1}{2}^+$	N or $N^*(1425)$	$M(1)$	1	0	$\cos^2\alpha$	1
(b)			$M(1)$	1	1	$\sin^2\alpha$	1
(c)	$\frac{3}{2}^+$	$N^*(1238)$	$M(1)$	1	1	$\sin^2\alpha$	$7+3x^2$
(d)			$M(1)$	1	2	$9-\cos^2\alpha$	$47-21x^2$
(e)	$\frac{3}{2}^-$	$N^*(1520)$	$E(1)$	0	1	$5-3\cos^2\alpha$	1

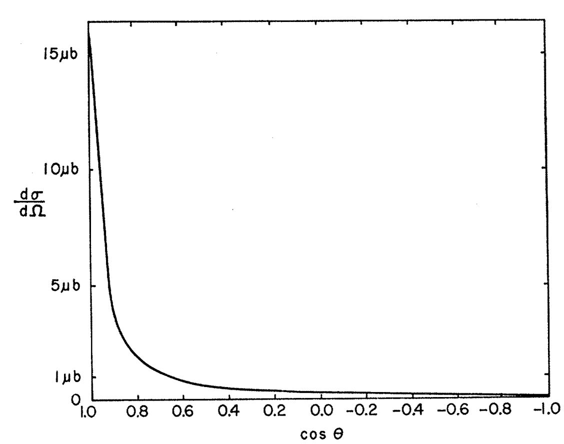


FIG. 7. The same distribution as in Fig. 5, but at a photon laboratory energy of 10 BeV.

[19] S. Barshay, Phys. Rev. Letters 17, 49 (1966).

characteristic experimental features summarized in the last paragraph of Sec. III.

ACKNOWLEDGMENTS

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APPENDIX

The electromagnetic interaction of neutral vector mesons may play an essential role in C-noninvariant vertices. For example, Lee[20] has shown that one may fail to have C, T invariance in a system of elementary neutral vector mesons with minimal electromagnetic couplings. This is, of course, not possible in a system of elementary spin-$\frac{1}{2}$ and spin-0 particles. A less specific reason is that the three physical neutral vector mesons, ϕ^0, ω^0, ρ^0 allow the effects of possible C-noninvariant electromagnetic interactions between members of *different* $SU(3)$ supermultiplets to be manifested in certain experimentally quite accessible processes (such as $\gamma+p\to\rho^0+p$), even in the limit of exact $SU(3)$ symmetry.[20] This circumstance is rather more difficult to achieve experimentally in the system of spin-$\frac{1}{2}$ baryons[21] or spin-0 mesons.[22]

It is well known that the C-noninvariant $\eta^0\pi^0\gamma$ vertex must vanish if the C-noninvariant electromagnetic interaction transforms like a unitary singlet or octet member, in the limit of $SU(3)$ symmetry. For example, let us *assume* that the neutral vector mesons play an essential role in C noninvariance and that this electromagnetic interaction transforms like F_3. Some mechanisms for inducing $\eta\to\pi$ effective C-noninvariant vertices are shown in Figs. 8 and 9, where the photon is, in general, virtual in Fig. 8, for a nonvanishing vertex. In these figures the top vertex is C noninvariant and all other vertices are assumed to be C invariant. Further, in these figures, the symbols ϕ^0, ω^0, ρ^0 represent the unitary singlet, and octet eighth and third components,

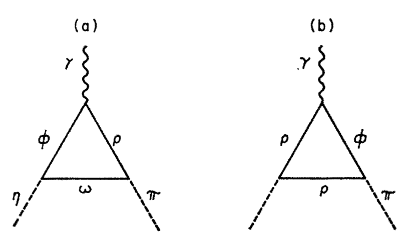

FIG. 8. Feynman graphs for a possible mechanism for inducing an effective $\eta^0\pi^0\gamma$ vertex. The C-noninvariant vertex is that involving the photon and two neutral vector mesons. In the figures, ϕ^0 represents a unitary singlet, and ω^0 and ρ^0 represent the eighth and third components of a unitary octet, respectively.

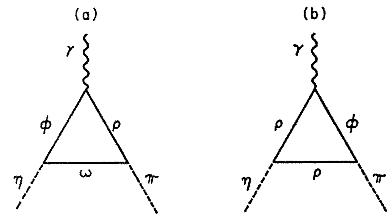

FIG. 9. Feynman graphs for a possible mechanism for inducing an effective $\eta^0\pi^0\rho^0$ vertex. The same remarks hold as for Fig. 8.

respectively, and the physical η^0 is assumed to be pure unitary octet (a sufficient approximation for the qualitative arguments that follow). Now in the limit of exact $SU(3)$ symmetry *and* mass degeneracy between ϕ^0 and ω^0, the matrix elements for the two Feynman graphs in Fig. 8 cancel when summed. The matrix element from the graphs in Fig. 9 also vanishes. In fact, $SU(3)$ symmetry is broken, but it is not clear whether this breaking leads to more prominent effects in the mechanism of Fig. 8 or that of Fig. 9, even though the matrix element for the latter involves an additional factor of $\sqrt{\alpha}\approx10^{-1}$. If the residual, $SU(3)$-breaking amplitude from the sum of the matrix elements for Fig. 8 were *more* than one order of magnitude smaller than $\alpha^{-1/2}$ times the $SU(3)$-breaking amplitude for Fig. 9, then the rate for $\eta\to\pi^0+e^++e^-$ from either the mechanism in Fig. 8 with $\gamma\to e^++e^-$, or from that in Fig. 9 with $\rho^0\to\gamma\to e^++e^-$, might not be expected to be much more than $10^{-3}-10^{-4}$ of the rate for $\eta\to2\gamma$. On the other hand, the mechanism in Fig. 9 with $\rho^0\to\pi^++\pi^-$ would control the $C=-1$ amplitudes in the decay $\eta\to\pi^++\pi^-+\pi^0$. Since the effective $\eta^0\pi^0\rho^0$ vertex is $O(\alpha)$, these amplitudes in interference with the $C=+1$ amplitudes [also $O(\alpha)$] can lead to a significant $\pi^+-\pi^-$ asymmetry (still relatively small because of barrier effects in the $C=-1$ states[23,24]).

The above model has a further consequence worth noting. If there were no additional and larger C-noninvariant mechanisms operating in the processes[3] (A) $\eta\to\pi^++\pi^-+\gamma$ and (B) $\eta\to2\pi^0+\gamma$ than that in Fig. 9 with $\rho\to\pi+\gamma$, one would expect little $\pi^+-\pi^-$ asymmetry in process (A) (perhaps $\approx10^{-2}$ that in $\eta\to\pi^++\pi^-+\pi^0$). Further, the rate for the completely C-noninvariant process (B) would be very small, with account taken of possible barrier effects, perhaps $\approx10^{-5}$ of the rate for process (A).

The above model is merely illustrative of a class of models in which C noninvariance is electromagnetic in origin and manifests itself in *certain* processes through C noninvariant *and isotopic spin* violating vertices among strongly interacting particles, which are $O(\alpha)$. Such vertices are indistinguishable from those that might arise from a C-noninvariant *and* isotopic-spin-violating part of strong interactions.[10,24,25] However, in the latter case the vertices would seemingly only accidentally be of order α [even if they are $SU(3)$-depressed by, say, $\sim10^{-1}$].

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