DEPARTURES FROM ONE-PION EXCHANGE IN 1.25-BeV π^--p INTERACTIONS*

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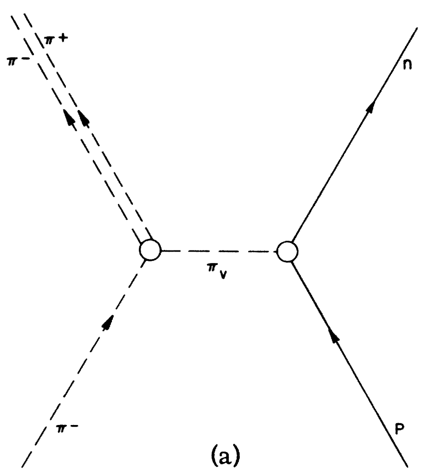
A rigorous test of One-Pion Exchange (OPE) has been suggested by Treiman and Yang.[1] We have applied the test to production of the ρ^0 meson ($\pi^+\pi^-$ resonance at $M_{+-} \simeq 740$ MeV, isospin $I=1$; spin, parity, and G parity $J=1^{--}$) by 1.25-BeV pions[2] in the reaction $\pi^- + p \to \pi^- + \pi^+ + n$. The test shows that, besides OPE, other mechanisms are important in the production, even for low momentum transfers. There are indications that the neutral ρ is distorted by the ω resonance.

Treiman and Yang pointed out that the nature of the OPE diagram [Fig. 1(a)] implies certain basic restrictions. Since the pion is spinless, its exchange can impart only kinematic information, and the planes formed by the particle trajectories at the two vertices must be uncorrelated. Figure 1(b) shows, in the rest frame of ρ^0, the planes and angles considered here. One plane is defined by the momenta of the virtual pion and the target proton, and the other plane is defined by the momenta of the virtual and scattered pions. The angle between these two planes is α, and the π-π scattering angle is θ. OPE requires that all cross sections be independent of α.

The distribution in α is indicated by the ratio f/b (number of events with $\alpha > 90°$/number of events with $\alpha \leq 90°$). The values of f/b for various ranges of four-momentum transfer, Δ, are given in Table I, for events inside the ρ peak ($700 \leq M_{+-} < 800$ MeV) and for events outside the peak. The observations show (a) for events inside the peak with $\Delta^2 < 0.30$ (BeV/c)^2, $f/b \simeq 1$, (b) for events inside the peak with $0.30 \leq \Delta^2 < 0.60$ (BeV/c)^2 and for events outside the peak with $\Delta^2 < 0.60$ (BeV/c)^2, there is an appreciable asymmetry ($f/b \neq 1$). The result (a) is consistent with OPE. Result (b) appears inconsistent with OPE, but no conclusions about the mechanism of ρ formation at high Δ^2 can be drawn in this experiment for the following reasons. The observed π^+ momenta indicate that events with $\Delta^2 > 0.30$ (BeV/c)^2 include, besides the ρ, contributions from the $\frac{3}{2}, \frac{3}{2}$ isobar, which are not clearly separable, for kinematic reasons, from the ρ events. Most of the asymmetry at high Δ^2 could be attributed to the isobar which, from considerations of G parity, cannot be formed by OPE.

Dependence of the $\pi\pi$-scattering angular distribution on α was examined. Figure 2 shows, for events of low Δ^2 inside the ρ peak, the values



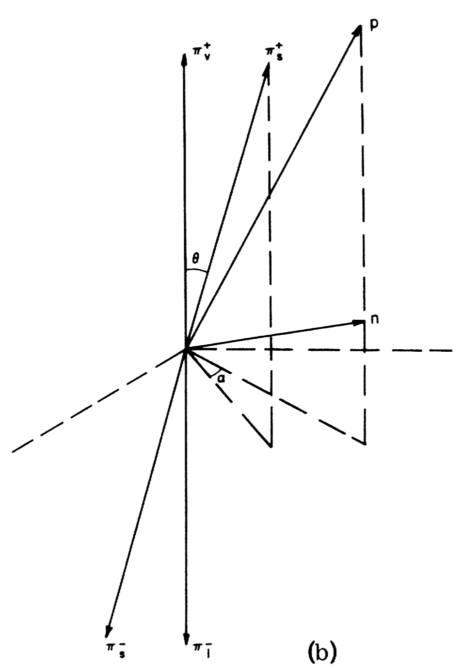


FIG. 1. (a) One-pion exchange diagram. (b) Coordinate system in $\pi^+\pi^-$ rest frame. The momenta of the incident and virtual pions are represented by π_i^- and π_v^+, the scattered pions π_s^- and π_s^+; p and n are the momenta of the target proton and recoil neutron.

Table I. Ratio of events with $\alpha < 90°$ to events with $\alpha \geq 90°$ (f/b).

Δ^2 $(\mathrm{BeV}/c)^2$	f/b $700 \leq M_{+-} < 800$ MeV	$M_{+-} < 700$ MeV and ≥ 800 MeV
<0.15	0.80 ± 0.15	0.71 ± 0.12
0.15 - 0.30	0.96 ± 0.19	0.76 ± 0.14
0.30 - 0.60	0.51 ± 0.12	0.68 ± 0.12
≥0.60	0.78 ± 0.17	0.84 ± 0.10

of the scattering asymmetry parameter $(F-B)/(F+B)$ for forward α and for backward α (F = number of pions scattered in the range $0 \leq \cos\theta < 1$, B = number of pions scattered in the range $-1 \leq \cos\theta < 0$). The distributions are markedly asymmetric for forward α but more nearly symmetric for backward α. For $\Delta^2 < 0.30$ $(\mathrm{BeV}/c)^2$, the asymmetry parameter is 0.40 ± 0.09 for forward α and 0.08 ± 0.09 for backward α. OPE requires the same distributions for forward and backward α; the consistency with OPE noted above ($f/b \simeq 1$) does not remain when this more sensitive angular scattering test is applied. Moreover, the

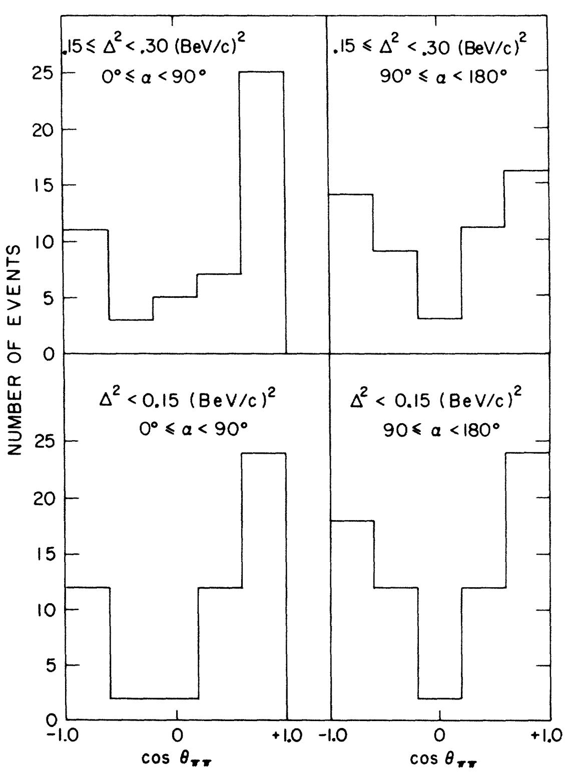


FIG. 2. π-π scattering angle θ as a function of α for events of small momentum transfer (Δ).

asymmetries in $\cos\theta$ distributions rule out a pure P state.

In Fig. 3(a) the asymmetry parameter is plotted for events of different $\pi\pi$ mass M_{+-}. The parameter remains positive throughout the resonance, and does not show the change of sign near the 740-MeV peak expected for interference of a P-wave resonance with S-wave background. Above 800 MeV the asymmetry parameter becomes negative; however, statistics in this mass range are limited by phase space. Curve (i) shows the asymmetry parameter calculated for a pure ρ with a small S-wave background (S-wave phase shift $\delta_0 \simeq 10°$).

One possible explanation[3] for the difference in $\cos\theta$ distributions for forward and backward α (Fig. 2) is that, besides ρ decays, the events include some two-pion ω decays, $\omega \rightarrow \pi^+\pi^-$. Production of ω in the reaction $\pi^- + p \rightarrow \omega + n$ is a non-OPE process, since, with quantum numbers $J = 1^{--}$, OPE is forbidden by G-parity conservation. It has been pointed out[4] that the G-forbidden two-pion decay of ω may be enhanced by electromagnetic interaction of ρ and ω resonances of the same spin and parity, and that this enhancement may be appreciable because of the small ω-ρ mass difference.

An ideogram of the $\pi^+\pi^-$ mass spectrum for $\Delta^2 < 0.30$ $(\mathrm{BeV}/c)^2$ [solid curve, Fig. 3(b)] shows departure from a simple Breit-Wigner resonance form. There is a suggestion of a second peak at the ω mass value, although the splitting is not certain statistically. The possibility of such structure in the ρ mass spectrum in $\bar{p}$-p annihilations has been reported by Button et al.,[5] and in 1.9-BeV/c π^--p interactions by West et al.[6]

The influence of ρ-ω mixing on the two-pion mass spectrum has been calculated from equations by Bernstein and Feinberg.[7] Masses and widths used were $M_\rho = 740$ MeV, $\Gamma_\rho = 110$ MeV, $M_\omega = 780$ MeV, and $\Gamma_\omega = 1$ MeV. Equal amplitudes[8] were assumed for initial production of pure ρ and ω. The magnitudes of the terms in the electromagnetic mixing parameter were taken to be ~1 MeV; this gives ~7% ratio of 2π to 3π ω decays. The experimental resolution (~±9 MeV at $M_{+-} = 750$ MeV) was folded into the calculation. The result of the calculation is shown by the dashed curve of Fig. 3(b). The curve is a satisfactory fit to the experimental distribution, within the limits of the available statistics and lack of precise values of ρ and ω masses and widths. A choice $\Gamma_\omega = 0.1$ MeV or 10 MeV also

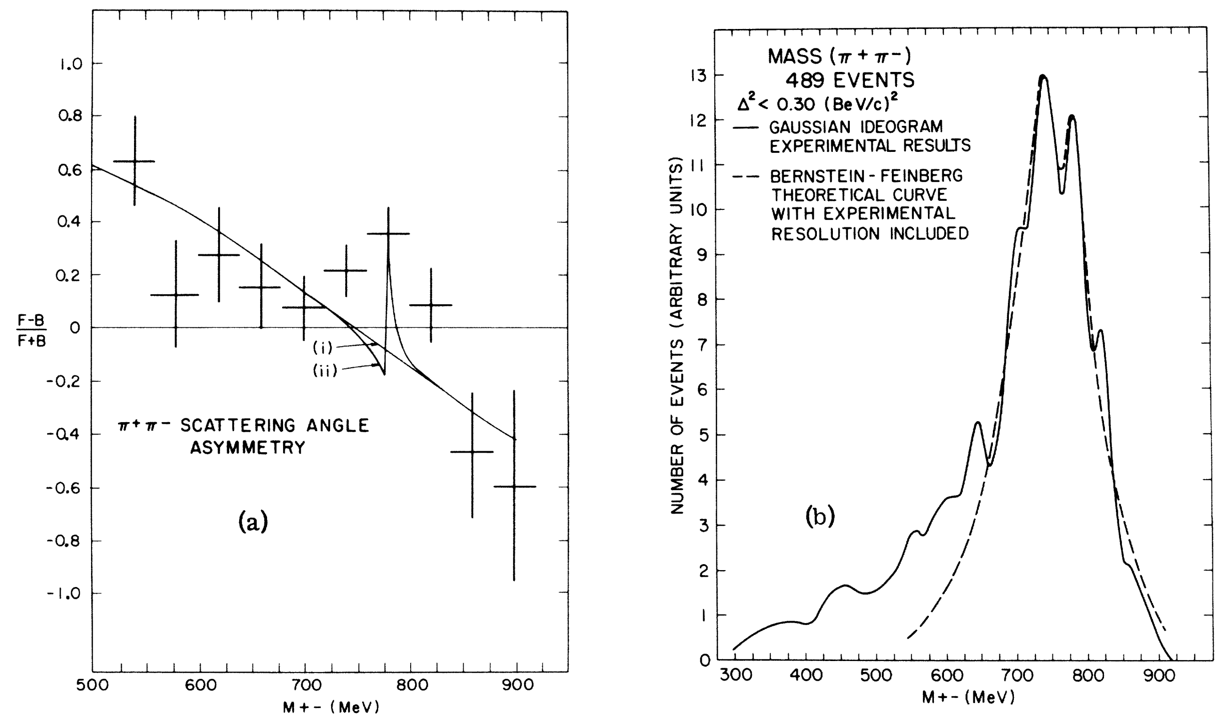


FIG. 3. (a) Scattering angle asymmetry parameter $(F-B)/(F+B)$ as a function of M_{+-} for $\Delta^2 < 0.30$ $(\mathrm{BeV}/c)^2$. Curve (*i*) shows the effect of interference of pure ρ with S-wave background, curve (*ii*) the effect of a $\rho-\omega$ mixture. (b) Gaussian ideogram of effective-mass distribution of $\pi^+\pi^-$ system for events with $\Delta^2 < 0.30$ $(\mathrm{BeV}/c)^2$. The dashed curve is calculated from the equation of Bernstein and Feinberg, and includes our experimental resolution.

gives a reasonable fit to the data, if the ratio of 2π to 3π decays of ω is kept constant by adjustment of the mixing parameter. Thus the shape of our experimental mass distribution is insensitive to the width of the ω resonance.

Whether $\rho-\omega$ mixing might possibly account for the asymmetry in $\pi\pi$-scattering angular distribution was investigated. The asymmetry parameter $(F-B)/(F+B)$ was computed from the differential cross section given by the equation,

$$\frac{\partial\sigma}{\partial\Omega} = 2\pi\bar{\lambda}^2 |\sin\delta_0 e^{-i\delta_0} + 3f(\rho,\omega)\cos\theta|^2,$$

where $f(\rho,\omega)$ is the Bernstein-Feinberg expression for $\rho-\omega$ mixture. The same masses, widths, and proportion of 2π to 3π decays used to compute the mass spectrum were used for this calculation. The result [curve (*ii*), Fig. 3(a)] shows a fluctuation from curve (*i*) in the vicinity of the resonance. Inclusion of the experimental resolution would flatten curve (*ii*) in this vicinity. A larger positive fluctuation, agreeing better with these measurements, would be given by a wider ω, but the present statistics do not justify a definite conclusion about the width.

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[3]Another possible explanation of the effect could be isobar contamination. Kinematically any $\frac{3}{2}, \frac{3}{2}$ $n\pi^-$-isobar formation would give pions in the region $\alpha \to 180°$ and $\cos\theta \to -1$. At low Δ^2 some isobar formation might result from rescattering of ρ-decay pions. Subtraction of isobar contamination would tend to make the $\cos\theta$ distributions more alike, although they would both be very asymmetric.

[4]S. L. Glashow, Phys. Rev. Letters 7, 469 (1961).

[5]J. Button, G. R. Kalbfleisch, G. R. Lynch, B. C. Maglic, A. H. Rosenfeld, and M. L. Stevenson, Lawrence Radiation Laboratory Report UCRL-9814 (1961).

[6]E. West, J. Bishop, J. Boyd, A. R. Erwin, D. Lyon, R. H. March, P. H. Satterbloom, and W. D.

Walker, Bull. Am. Phys. Soc. 7, 281 (1962). The crucial sentence should be corrected (private communication, A. R. Erwin) to read "The ρ appears to have a double peak in Reaction (a)."

[7]J. Bernstein and G. Feinberg, Brookhaven National Laboratory Report BNL-6122, 1962 (to be published). The M_{+-} distribution was calculated from their Eq. (29). Initial pure states of ρ and ω are assumed.

[8]After correcting for background events, we obtain a cross section for ρ^0 production in the present experiment of approximately 3.1 mb. Our cross section for the process $\pi^- + p \to \pi^- + \pi^+ + 2$ or more neutrals gives an upper limit of 3.8 ± .2 mb to the cross section for ω production, $\pi^- + p \to \omega + n$. This cross section cannot be measured in this experiment, since for the three-pion decay there are two neutrals in the final state. Toohig et al., preprint (report to the International Conference on High Energy Physics at CERN, Geneva, Switzerland, 1962) give a cross section of 1.4 ± 0.4 mb for ω production in the charge-symmetric $\pi^+ + n \to \omega + p$. At our higher energy, a somewhat higher cross section would be expected, and so we have assumed the ρ- and ω-production cross sections to be equal. We have also assumed this equality to apply in the momentum transfer $\Delta^2 < 0.30$ (BeV/c)^2. The calculation is not sensitive to the exact ratio of the cross sections for ρ and ω production.

STUDY OF PION-PION INTERACTIONS FROM PION PRODUCTION BY PIONS*

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Recent experiments on pion production have shown the presence of a strong pion-pion interaction in the isotopic-spin-one state.[1-3] These experiments have established the existence of a resonance (the ρ meson) at an ω value of 750 MeV, where ω is the total energy of the two pions in their barycentric frame. The full width at half maximum of the resonance is approximately 130 MeV.[2] In these experiments, pions were scattered from protons in a hydrogen bubble chamber. Of the two groups of reactions,

$$\pi^\pm + p \to \pi^\pm + \pi^0 + p \tag{a}$$

and

$$\pi^\pm + p \to \pi^\pm + \pi^+ + n, \tag{b}$$

(a) has received the most attention because a measurement of the recoil proton fixes ω^2 and Δ^2 (where Δ is the four-momentum transfer from the initial- to the final-state nucleon) for an event of the desired type. An extrapolation procedure for analyzing these experiments, suggested by Chew and Low,[4] involves the study of those collisions in which Δ^2 is small. It was postulated that, for small Δ^2, the one-pion exchange interaction would predominate. To date, several experimenters[3,5] have reported some success in analyzing the pion-pion interaction by the extrapolation method.

In the experiment reported here, we study Reactions (b) with an incident pion momentum of 1.75 BeV/c. We find evidence of a pion-pion interaction in the $(\pi^+\pi^-)$ system (which contains isotopic-spin components 0, 1, and 2), although the extrapolation method of analysis appears to fail. The $(\pi^+\pi^+)$ system (pure isotopic-spin 2) shows no comparable resonant state. There is strong evidence for processes other than the one-pion exchange even at relatively low momentum transfers.

Negative and positive pion beams were produced from a beryllium target placed in an almost field-free region of the Bevatron primary beam. They were formed into an external beam and focussed onto a 10-cm-thick liquid-hydrogen target. Detection apparatus consisted of plastic scintillation counters and their associated equipment. The counters were arranged in two groups. The main group consisted of 84 trapezoidal prisms arranged to fit on a section of the surface of a sphere of 160-cm radius with the hydrogen target at its center. Looking from the target at the counter array, one would see the elements grouped in a series of seven concentric rings. Each ring subtended a polar-angular interval of 8 deg. The array extended from 4 to 60 deg. The rings were divided into 12 elements, each with a 30-deg azimuthal angle. All the counters were 15 cm thick in order to be effective in detecting neutrons by recoil protons and inelastic reactions on carbon. Each counter element was coupled to a photomultiplier tube by a hollow aluminum light guide. The second group of counters was 1.0 cm thick and was designed to detect pions that emerged at scattering angles