EVIDENCE FOR VECTOR-MESON EFFECTS ON π^0 PHOTOPRODUCTION FROM HYDROGEN*

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We have measured angular distributions of the reaction

$$\gamma + p \rightarrow p + \pi^0,$$

in hopes of isolating the contribution of the virtual exchange of one neutral vector meson. The possibility of doing this has been pointed out by many people and is explained by Moravcsik.[1] We find evidence that above the third pion-nucleon resonance such a "pole" process does become important or even dominant. This behavior could be caused by a meson of spin one which has either parity and any isotopic spin. This means that the effect is due to any combination of heavy mesons ω, ρ, η (if it has spin 1), or ζ (if it exists). If a single meson dominates (ω or η is a likely candidate), we can obtain the relevant coupling constants as will be explained.

The data which we are reporting consist of angular distributions in the forward hemisphere at laboratory-incident photon energies (K) of 740, 910, and 1140 MeV. In the past, experimental studies of this reaction have relied chiefly on the detection of the recoil proton, with perhaps one of the π^0-decay photons being also observed.[2] For our purposes the most important region is that of very forward-going π^0's. Since these π^0's are accompanied by very low-energy protons, which are hard to work with, we have resorted to detecting and measuring the π^0's, although, where convenient, we have also detected the recoil proton.

With the bremsstrahlung beam of the Caltech electron synchrotron indicent on a 16-cm-long liquid-hydrogen target, an emergent π^0 was detected by the fast (~15 nsec) time coincidence of the two photon pulses resulting from its decay. These photons were absorbed in two lead-glass Čerenkov counters (36×36×30 cm) described elsewhere,[3] which were mounted, one above the other, on a trolley which could be rotated horizontally about the target (which was some 200 cm distant). Apertures were defined as 15×20-cm holes in 29-cm-thick lead walls with the apertures being backed by anticoincidence counters. When the recoil protons were being counted, it was with a 15×20-cm scintillator 75 cm from the target, and the anticoincidence counters behind the apertures were not used. For the most forward angles, the target was placed in a sweeping magnetic field which bent pair-produced electrons horizontally away from the counters to reduce single-counter rates.

The kinematics of an individual event were determined as follows. The π^0 laboratory production angle (± about 2°) was given by the horizontal counter position. The incident photon energy was limited above by the bremsstrahlung end point and below by the relative position of the photon counters, which, for π^0 energies below some minimum, were too close to catch both decay photons. The incident energy-resolution function had, typically, a width of 150 MeV. Rather poor energy resolution is implicit in this method of measuring this reaction.

The photon counters were energy sensitive, measuring the two photon energies to be $K_1 \pm \Delta K_1$ and $K_2 \pm \Delta K_2$. ($\Delta K_1/K_1 = 0.08/K_1^{1/2}$ with K_1 in BeV, and similarly for K_2.) The chief use of this pulse-height information is illustrated in Fig. 1, which, for a typical point with protons not detected, is a distribution in $E_\pi = K_1 + K_2$. Agreement between the smooth curve, which is the expected response to the foreground process alone, and the histogram, which was observed, yields a consistency check on the experiment. Also one can see that there was a background of coincident photons (perhaps from $\gamma + p \rightarrow p + \pi^0 + \pi^0$) which could be

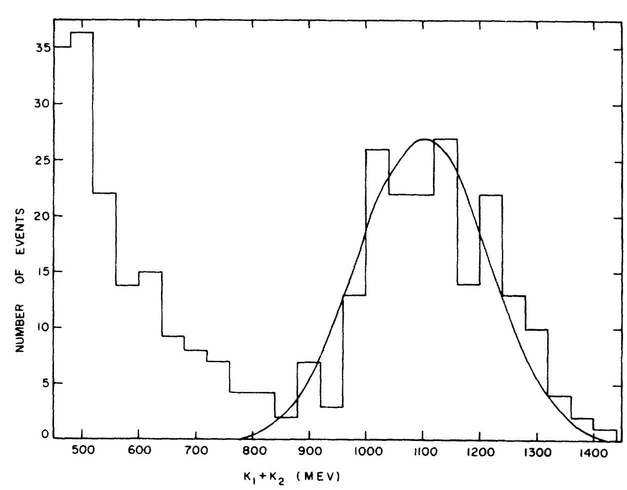

FIG. 1. Spectra of the sum of the energies (K_1 and K_2) of coincident photons for a typical configuration, as measured (histogram) and as expected from π^0's only (solid curve).

discarded without serious error because of their low $K_1 + K_2$. The separation was less clean at the most forward angles, largely because of the small cross section.

For a given counter configuration, a somewhat complicated calculation is required to transform the counting rate into a differential cross section. This has been done independently by a Monte Carlo method and by an approximate analytic method. Since these calculations disagree by about 5 percent, a systematic error of that amount from this source is possible. The probability, having counted a π^0, of also detecting the recoil proton varied between $\frac{1}{2}$ and 1.

Corrections to the data have been made for the following effects: γ-ray absorption (less than 6 percent), proton absorption (less than 11 percent), and electronic dead time (less than 15 percent). Empty target backgrounds which were typically ten percent and one percent without and with protons, respectively, have been subtracted.

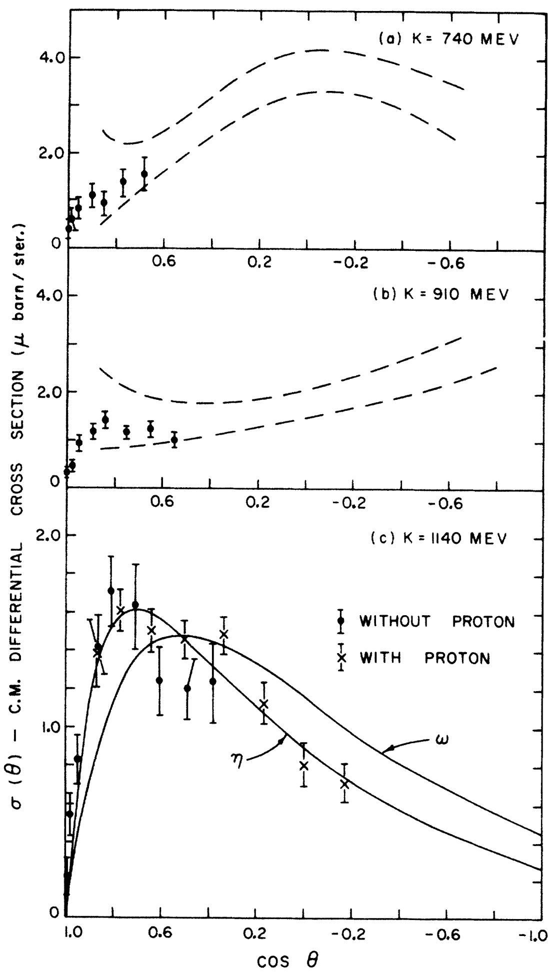

FIG. 2. Differential cross sections for the reaction $\gamma + p \rightarrow p + \pi^0$. The dashed lines represent limits within which most of the earlier measurements lie. The solid curves are one-parameter least-squares fits as described in the text. Note the expanded scale of (c).

Our results are plotted in Fig. 2. The error bars have been compounded from three nonsystematic sources: counting statistics, errors in making electronic dead-time corrections, and an error due to uncertainty in the synchrotron end-point energy. A systematic error of ten percent also arises from the third source.

Moravcsik, analyzing data which is crudely indicated by the broken limiting curves of Figs. 2(a) and 2(b), and other data at lower energy, concluded that any vector-meson effects were too small to be observed. With the added data of this experiment at 740 and 910 MeV, we have repeated his analysis and find results which, though consistent with, are less convincing than our analysis of the 1140-MeV data of Fig. 2(c). Hence we discuss only these data.

The striking feature which we wish to point out is the resemblance between the measurements and the smooth curves of Fig. 2(c). These are one-parameter least-squares fits to the data with the fitting function being $\phi(M, \theta)$ which is the cross section corresponding to the diagram of Fig. 3(a) where M is the mass of the exchanged meson and θ is the c.m. π^0 angle. M was taken as 790 and 550 MeV for the curves marked ω and η, respectively. An adequate approximation is

$$\phi(M, \theta) = \Gamma_{\omega, \eta \rightarrow \pi^0 + \gamma} \left(\frac{\gamma_{\omega NN, \eta NN}}{4\pi} \right)^2 \frac{9}{M_{\omega, \eta}^{\;3}} \frac{\sin^2\theta}{(\cos\theta - \cos\theta_0)^2}, \tag{1}$$

where $\cos\theta_0$ is the (unphysical) position of the

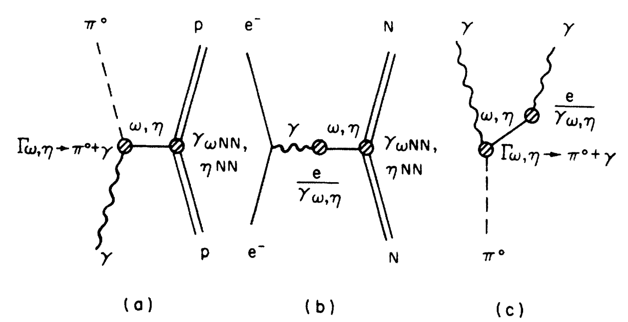

FIG. 3. Feynman diagrams suggesting a procedure for determining the coupling constants $\Gamma_{\omega \rightarrow \pi^0 + \gamma}$, $\gamma_{\omega NN}$, and γ_ω (or $\Gamma_{\eta \rightarrow \pi^0 + \gamma}$, $\gamma_{\eta NN}$, and γ_η) as described by Gell-Mann and Zachariasen (reference 4).

pole, and where the coupling constants are defined by Gell-Mann and Zachariasen.[4]

If we take this as showing the existence of such a pole, we are left with the problem of determining which vector mesons are contributing. The situation is still too complicated to proceed rigorously but, partly for illustrative purposes, we investigate two simple hypotheses: (1) The η has spin 1 and completely dominates our data. (2) The ω completely dominates our data.

In support of either of these hypotheses we can make the following comments. The evidence for the existence of the ζ is somewhat tentative. Evidence of Ruderman et al.[5] on the coherent photoproduction of π^0's from complex nuclei indicates that at least a large portion of the polelike behavior which we observe comes from the exchange of a $T=0$ vector meson. In the unitary symmetry scheme of Gell-Mann,[6] the cross section with the ω exchanged is expected to be three times as large as that with the ρ exchanged.

The evidence of Rosenfeld et al.,[7] which tends to indicate that the spin of the η is 0, argues against our first hypothesis. As is clear from our Fig. 2(c), however, our data is more easily interpretable with the lower mass of 550 MeV for the exchanged meson, and, hence, we consider this possibility.

As shown by Eq. (1), we can obtain from our data a value for the product of coupling constants $\Gamma_{\omega,\eta\to\pi^0+\gamma}(\gamma_{\omega NN,\eta NN}^2/4\pi)$. We have done this, following Moravcsik, by making least-squares fits to the data multiplied by $(\cos\theta-\cos\theta_0)^2$, with fitting functions $\sum_0^n A_i\cos^i\theta$ and extrapolating to the pole. For mass 550 MeV, this prescription unambiguously yields $\Gamma_{\eta\to\pi^0+\gamma}(\gamma_{\eta NN}^2/4\pi)=60\pm4$ keV.[8] For ω's we get good fits with $n\geq3$ and as the value of $\Gamma_{\omega\to\pi^0+\gamma}(\gamma_{\omega NN}^2/4\pi)$ we obtain 0.63 ± 0.06 MeV for $n=3$, and 0.98 ± 0.21 MeV for $n=4$. We must warn that in this case the extrapolation is quite daring, the pole being at $\cos\theta=1.84$, and that the quoted errors, although well defined,[8] are only weakly related to our actual ignorance of the coupling constant in question, even under our hypotheses. The degree to which the $n=3$ and the $n=4$ values disagree is a better indication of the actual error.

Given that we know the value of the product $\Gamma_{\omega\to\pi^0+\gamma}(\gamma_{\omega NN}^2/4\pi)$ (which we take to be 0.67 MeV), and knowing one of the isoscalar electromagnetic form factors and the π^0 lifetime, Gell-Mann and Zachariasen have given a prescription for calculating $\Gamma_{\omega\to\pi+\gamma}$ and $\gamma_{\omega NN}$ (as well as another coupling constant γ_ω) individually. This possibility is illustrated in Fig. 3. Figure 3(a) implies our Eq. (1), while Figs. 3(b) and 3(c) imply Eq. (4.22) of reference 4,

$$F_1^S(s)\approx\left(\frac{\gamma_{\omega NN}}{\gamma_\omega}\right)\left(\frac{-M_\omega^2}{s-M_\omega^2}\right)+\left(1-\frac{\gamma_{\omega NN}}{\gamma_\omega}\right), \qquad (2)$$

and Eq. (5.12)[9] of reference 4,

$$\frac{\Gamma_{\omega\to\pi^0+\gamma}}{\Gamma_{\pi^0\to\gamma+\gamma}}=2\left(\frac{M_\omega^2-\mu^2}{M_\omega\mu}\right)^3\left(\frac{\gamma_\omega}{e}\right)^2. \qquad (3)$$

Taking $\gamma_{\omega NN}/\gamma_\omega$ as[10] 1.2 and the π^0 lifetime as 1.9×10^{-16} sec,[11] and solving the three equations, we get $\gamma_\omega^2/4\pi=1.6$, $\gamma_{\omega NN}^2/4\pi=2.3$, and $\Gamma_{\omega\to\pi^0+\gamma}=280$ keV.

If we return to our other hypothesis, we can solve the same triplet with ω replaced by η and (using[12] $\gamma_{\eta NN}/\gamma_\eta=1.2$) get $\gamma_{\eta NN}^2/4\pi=1.3$, $\gamma_\eta^2/4\pi=0.88$, and $\Gamma_{\eta\to\pi^0+\gamma}=47$ keV.

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[4]M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[5]H. Ruderman, R. Gomez, R. M. Talman, and A. V. Tollestrup (to be published). The amplitudes for photoproducing a π^0 from a proton and from a neutron are equal when a $T=0$ vector meson is virtually exchanged, while they are equal but of opposite sign when a $T=1$ meson is exchanged. Hence, in the former case, but not in the latter, this process results in a large coherent production near 0° from complex nuclei. Such an enhancement is, indeed, observed. While this could arise from any process having a large non-spin-flip cross section near 0° and coherent from neutrons and protons, the magnitude is roughly correct to correspond to our measurement from protons, if the exchanged meson has $T=0$. Unfortunately, a precise comparison is difficult because of the nuclear physics involved.

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[8]The errors quoted here and subsequently are those statistical errors which arise naturally in the least-squares analysis of the data of Fig. 2. As such they

do not include our systematic error of 15 percent or any estimate of the error caused by any expected partial incorrectness of our assumptions.

[9]This equation has been changed by a factor of 4, by which it was incorrect in the original.

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POSSIBLE RESONANCES IN THE $\Xi\pi$ AND $K\bar{K}$ SYSTEMS*

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The purpose of this note is to report the existence of marked departures from phase space in the effective-mass distributions for the $\Xi\pi$ and $K\bar{K}$ states. We present evidence that, in about 25% of the events observed, the $\Xi\pi$ state results from the decay of a resonant state (Ξ^*) with a mass of 1535 MeV and a full width of <35 MeV. The observed anomaly in the $K\bar{K}$ effective-mass distribution is possibly open to different interpretations. If we assume it to be due to the decay of a resonant state K^*, we find that M_{K^*} $=1020$ MeV, and that it has a full width of 20 MeV. However, it may also be possible to explain the effect as due to S-wave $K\bar{K}$ scattering. These results, as well as preliminary evidence concerning the properties of the Ξ^* and K^*, are discussed below.

The data for this experiment were obtained in an exposure of the BNL 20-in. hydrogen bubble chamber at the Brookhaven AGS. Details of the exposure and beam have been previously discussed.[1] Data were obtained both at 2.24 and 2.5 BeV/c. The sample reported on here consists of 79 $\Xi\pi$ and 37 $K\bar{K}$ combinations from the following production modes:

$$K^- + p \to \Xi^- + \pi^+ + K^0 \quad (1a)$$
$$\Xi^- + \pi^0 + K^+ \quad (1b)$$
$$\Xi^0 + \pi^- + K^+ \quad (1c)$$
$$\Xi^0 + \pi^0 + K^0 \quad (1d)$$
$$\to \Lambda + \bar{K}^0 + K^0 \quad (2a)$$
$$\Lambda + K^- + K^+ \quad (2b)$$

All events were measured and analyzed using the BNL TRED-KICK system. Except for Reaction (1d),[2] we believe the contamination from other topologically similar event types to be negligible.

For each of the above reaction types, the distributions of the square of the effective mass, defined by

$$M_{\rm eff}^2 = [(\textstyle\sum_i E_i)^2 - (\sum_i \vec{p}_i)^2],$$

were obtained. The results are shown in Figs. 1 and 2 in the form of Dalitz plots with $M_{\rm eff}^2$ distributions projected onto the appropriate axes. The departures from the phase-space predictions are 3 standard deviations for the $\Xi\pi$ and 2.5 standard deviations for the $K\bar{K}$ effective-mass-squared distribution. This estimate of error is based on the square root of the total number of events in the bins containing the peaks in the $\Xi\pi$ and the $K\bar{K}$ Dalitz plots (see Figs. 1 and 2). Note

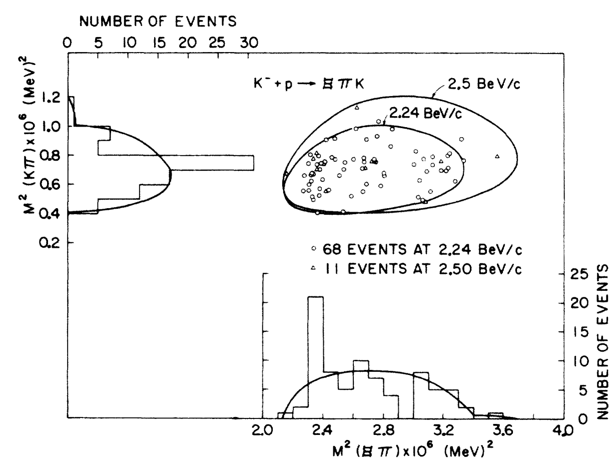

FIG. 1. The Dalitz plot for the channel $\Xi\pi K$ projected on the $M^2(K\pi)$ and the $M^2(\Xi\pi)$ axes. The solid curves on the projections are the invariant phase-space curves normalized to the total number of events.