on the hypothetical reaction

$$\nu_e + e^- \rightarrow \nu_e + e^-, \qquad (12)$$

we find, using expressions for the total cross section of Reaction (12) given in the literature,[16]

$$\int \sigma(\nu_e + e^-)\varphi(^8\mathrm{B})d\nu = 2.5\times10^{-36}\ \mathrm{sec}^{-1} \qquad (13)$$

per target electron.

We wish to thank Professor T. L. Jenkins for stimulating discussions and correspondence, and for transmitting the results of an independent numerical computation of our results. We would also like to acknowledge interesting discussions with Dr. Howard Reiss.

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[1]H. A. Bethe, Phys. Rev. 55, 434 (1939).

[2]J. N. Bahcall, Science 147, 115 (1965).

[3]V. A. Kuzmin, Phys. Letters 17, 27 (1965), recently mentioned neutrinos from $H^1 + He^3 \rightarrow He^4 + e^+ + \nu_e$ with an end point of 18.8 MeV. It is not clear whether their flux is big enough to compete with Reaction (2), which has a flux of $2.5\times10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ (Carl Werntz, private communication).

[4]R. Davis, Phys. Rev. Letters 12, 303 (1964); F. Reines and W. R. Kropp, Phys. Rev. Letters 12, 457 (1964).

[5]R. Davis and D. S. Harmer, based on $\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$.

[6]T. L. Jenkins, to be published.

[7]J. Weneser, Phys. Rev. 105, 1335 (1957), gave a theoretical calculation on $\bar{\nu}_e + H^2 \rightarrow 2n + e^+$, with a two-neutron final state; the threshold is at 4.04 MeV. With the two-component neutrinos used in the present work, Weneser's cross section must be multiplied by 2.

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[9]See also H. Überall and L. Wolfenstein, Nuovo Cimento 10, 136 (1958).

[10]M. A. Preston, Physics of the Nucleus (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1962).

[11]A. Erdélyi, Higher Transcendental Functions (McGraw-Hill Publishing Company, Inc., New York, 1953).

[12]P. M. Morse and H. Feshbach, Methods of Theoretical Physics (McGraw-Hill Publishing Company, Inc., New York, 1953).

[13]Obtained by setting $e \rightarrow 0$, i.e., $R^{-1}h(\eta) \rightarrow 0$, $\eta \rightarrow 0$ and keeping all other parameters unchanged.

[14]We used, like Weneser, the value $a_s = -23.8\times10^{-13}$ cm (the experimental n-p scattering length) for the n-n scattering length needed in the antineutrino reaction.

[15]J. N. Bahcall, Phys. Rev. Letters 12, 300 (1964).

[16]See, e.g., J. N. Bahcall, Phys. Rev. 136, B1164 (1965).

π^+ CHARGE FORM FACTOR AND ELECTROPRODUCTION*

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We report e-π coincidence measurements on the electroproduction reaction $e^- + p \rightarrow e^- + n + \pi^+$ with kinematic conditions chosen to maximize the contribution from the exchange of longitudinally polarized photons. The yield is sensitive to the charge form factor of the pion, and the data have been compared with a theoretical model with the conclusion that the pion charge structure is not very different from that of the proton.

The electroproduction of a pion is assumed to take place through the exchange of a single photon.[1] Figure 1 illustrates the kinematic definitions we will use (in general, lower case letters refer to the laboratory frame, capitals denote the corresponding quantities measured in the final pion-nucleon rest frame). We wish to maximize the effect of the pion-pion amplitude corresponding to the direct absorption of the virtual photon by a virtual charged pion emitted by the target proton. The pole occurs at $(q-k)^2 - \mu^2 = 0$, or $\cos\Theta = 1/\beta_\pi$, so we should expect the largest contribution in the physical region at $\Theta = 0$, that is, for pions emitted forward along the momentum-transfer direction $\vec{K}$. Transversely polarized photons cannot transfer their helicity to forward-going pions, so at $\Theta = 0$ the pion pole can contribute only when the photon is longitudinally polarized. Furthermore, since the dominant 33 resonance contributes mainly to the magnetic dipole amplitude (a transverse multipole), the pion-pole term does not have to compete with the resonance in the longitudinal part of the electroproduction yield

Fortunately the contributions of transversely and longitudinally polarized virtual photons are readily separable experimentally in the

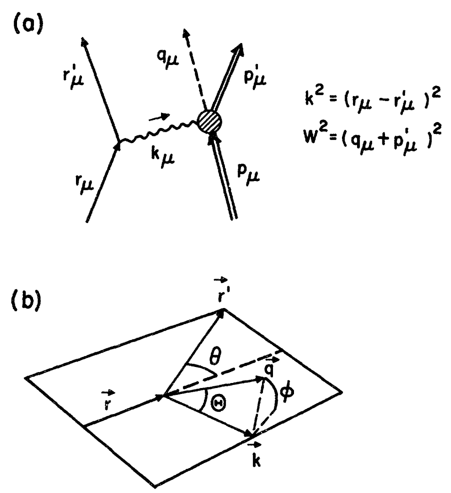

FIG. 1. (a) Diagram for the reaction $e+N\rightarrow e+N+\pi$ assuming single-photon exchange. (b) A view of the momentum vectors in the laboratory frame illustrating the angle definitions used in this paper. Although the angle Θ between the pion momentum and the momentum transfer vector $\vec{k}$ is shown here in the lab frame, Θ is referred to the pion-nucleon center-of-mass frame throughout the text.

case of pions detected along the momentum-transfer direction, since at $\Theta=0$ the electroproduction differential cross section can be written[2] in the form

$$d^3\sigma/dE'd\omega d\Omega=\Gamma_T[T(k^2,W)+\epsilon L(k^2,W)],$$

where

$$\Gamma_T=\frac{\alpha}{4\pi^2}\frac{E'}{E}\frac{W^2-M^2}{2M(-k^2)}\left(2+\frac{-k^2}{\vec{k}^2}\cot^2\frac{\theta}{2}\right),$$

a known function of the kinematic variables. In the above formulas E and E' are the incident and scattered electron lab energies; $d\omega$ is the electron lab solid-angle differential; $d\Omega$ is the pion solid angle in the pion-nucleon rest frame; and

$$\epsilon=[(-k^2/\vec{k}^2)\cot^2(\theta/2)][2+(-k^2/\vec{k}^2)\cot^2(\theta/2)]^{-1}$$

is the polarization of the exchanged photon (transverse and longitudinal) in the pion-nucleon frame. The polarization ϵ is mainly dependent on the electron lab angle (for fixed k^2 and W), and varies from $\epsilon=1.0$ at $\theta\rightarrow 0$ to $\epsilon=0$ at $\theta=180°$. At $\Theta=0$ the φ-dependent terms in the cross section[1] vanish, and T and L are functions only of k^2, the invariant four-momentum transfer (negative here), and W, the total pion-nucleon center-of-mass energy.[3] In the limit $k^2\rightarrow 0$, T approaches $d\sigma/d\Omega(\gamma+p\rightarrow n+\pi^+;\ W;\ \Theta=0)$, while L approaches zero.

No new techniques were involved in the experiment. At the peak of the acceleration cycle, the internal circulating electron beam of the Cornell 2-GeV synchrotron struck a liquid-hydrogen target mounted in the synchrotron vacuum chamber. The flux was monitored by observing the forward bremsstrahlung yield with a Quantameter.[4] Scattered electrons were magnetically analyzed and detected using a quadrupole spectrometer and counter telescope as in previous Cornell experiments.[5] Electroproduced pions were detected in coincidence by a similar spectrometer system on the other side of the beam. Throughout the experiment the pion-photon angle was fixed at $\Theta=0$, while E, E', and θ were always adjusted so that $-k^2=2.96\ \mathrm{F}^{-2}=0.115\ (\mathrm{GeV}/c)^2$ according to the relation $k^2=-2EE'(1-\cos\theta)$. Data were taken for two values of W, 1210 and 1313 MeV [given by $W^2=M^2+k^2+2M(E-E')$]. Each data point was repeated at several electron lab angles ($\theta=15°$, $30°$, $55°$ at $W=1210$ MeV and $\theta=15°$, $30°$ at $W=1313$ MeV),[6] thus giving a range in photon polarization ϵ from 0.45 to 0.93. Incident energies E varied from 600 to 1600 MeV.

The 20-MeV sensitive range in W was set by the pion-spectrometer momentum resolution (7% full width at half-maximum) and was overmatched on the electron side. The electron momentum aperture (10% full width at half-maximum) was split into three counting channels to provide a continuous check on the momentum matching. The solid-angle apertures (5 msr on both sides) were split into four coincidence channels to check that the yield was not varying rapidly over the detected angular range. All data were normalized to elastic electron-proton scattering yields measured in the electron spectrometer with the same incident energy. After normalizing, the significant systematic errors come mainly from uncertainties in the pion apertures Δq and $\Delta\Omega$ and the effect of the 0.0005-inch polyimide target wall. The combined systematic error is strongly correlated from one data point to another and is estimated to be less than 9% in the normalized electroproduction cross sections. With a beam duty cycle of about 1% and a coincidence resolving time of about 2 nsec, accidental coincidences were not a serious problem, although the true coincidence rates were typically very low. Data were corrected for pion decay and absorption and for radiative effects.[7] To check the experimental method and the interpretation of the results, we also measured electron-proton coincidences under the same conditions, corresponding to π^0 electroproduction at $\Theta = 180°$.

The data are plotted in Fig. 2 in the form of the reduced cross section

$$\frac{1}{\Gamma_T}\frac{d^2\sigma}{dE'd\omega d\Omega}$$

vs $\epsilon(\theta)$, the photon polarization parameter. The single-photon-exchange assumption implies a straight-line behavior, with an intercept equal to the transverse contribution T and a slope equal to L, the longitudinal term. The prominent slope in the π^+ data clearly show the presence of an appreciable longitudinal effect; indeed both plots are consistent with zero transverse contribution.

In order to draw any quantitative conclusions about $F_\pi(k^2)$ the charge form factor of the π^+,

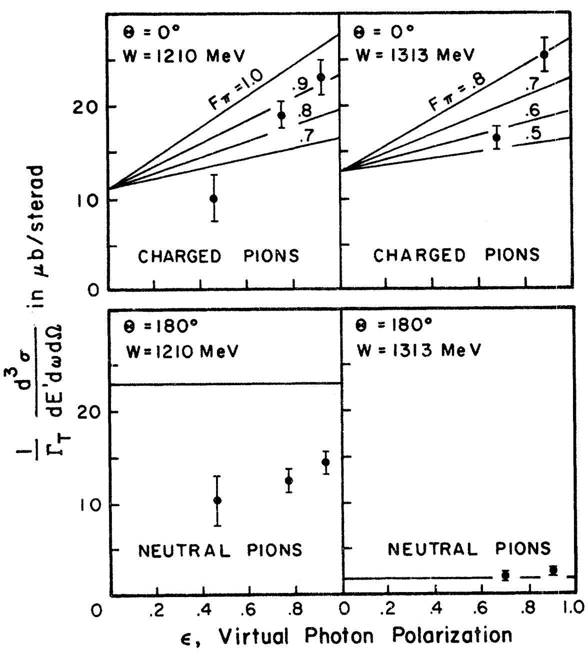

FIG. 2. The reduced experimental cross sections plotted against the photon polarization parameter. Only the statistical counting errors are indicated. There is an estimated 9% systematic uncertainty in the overall scale factor. For all of the data $k^2 = -2.96$ F^{-2}. The straight lines indicate the predictions of Fubini et al.[8] for various assumptions about the value of the pion-charge form factor. The backward π^0 predictions are independent of F_π.

we must resort to a dynamical model. The calculation of Fubini, Nambu, and Wataghin[8] has been successful in interpreting the results of inelastic electron-scattering experiments,[9] integrated over pion directions. It is an extension to electroproduction of the photoproduction theory of Chew, Goldberger, Low, and Nambu.[10] It is based on the Born approximation plus the assumption that the 33 resonance dominates the dispersion integrals. Their longitudinal contribution comes entirely from the Born terms, involving $F_\pi(k^2)$ in the pion-pole term and the gauge term,[11] while the transverse is dominated by the resonance and the nucleon Born terms. The prediction of Fubini et al. is indicated by the straight lines in Fig. 2, showing the sensitivity to F_π. The predicted yield of backward π^0 is purely transverse, in accord with the data, but at $W = 1210$ MeV, the predicted cross section (dominated by the resonance) appears to be about a factor of 2 too large.[12] Best fits to the forward π^+ data are obtained for $F_\pi(-2.96\ \mathrm{F}^{-2}) = 0.87 \pm 0.04$ and 0.66 $\pm$ 0.04 (statistical errors only) for $W = 1210$ and 1313 MeV, respectively, although large χ^2 values (6.6 and 8.5) indicate either that the theory is inadequate[13] or that there are large unknown systematic errors in the data. Our estimated 9% systematic scale uncertainty in the data can account for only part of the χ^2.

If, however, we assume (and this is crucial) that the prediction of Fubini et al. is exact, the weighted average of the two fits ($W = 1210$ and 1313 MeV) gives a pion charge form factor[14]

$$F_\pi(-2.96\ \mathrm{F}^{-2}) = 0.76 \pm 0.14.$$

The quoted uncertainty is determined from the rms deviation of the two measurements from the mean. For comparison, the proton-charge form factor at the same momentum transfer[15] is about 0.74. Assuming a linear k^2 dependence of F_π out to -3 F^{-2}, we can express our result in terms of the rms charge radius of the pion:

$$r_\pi = 0.70 \pm 0.20\ \mathrm{F}.$$

If we assume that the photon couples to the pion through the exchange of a single $T = 1$ vector meson, that is $F_\pi(k^2) = (1-k^2/m^2)^{-1}$, then the mass of the meson turns out to be

$$m = 600^{+400}_{-100}\ \mathrm{MeV}.$$

which is not inconsistent with ρ^0 dominance.

We are indebted to M. Tigner for assistance in setting up the experiment and to D. R. Yennie, S. L. Adler, and C. Mistretta for valuable conversations on the interpretation of the data.

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[2]R. H. Dalitz and D. R. Yennie, Phys. Rev. 105, 1598 (1957); M. Gourdin, Nuovo Cimento 21, 1094 (1961); L. N. Hand, thesis, Stanford University, 1961 (unpublished); S. M. Berman, Phys. Rev. 135, B1249 (1964); see also Ref. 1.

[3]In terms of the σ_U and σ_L defined in Ref. 1, T and L are given by $T=(\sigma_U 2M|\vec{k}|)(W^2-M^2)^{-1}$ and $L=(-\sigma_L 2M|\vec{k}|k^2)(W^2-M^2)^{-1}K_0^{-2}$. Both T and L are positive definite.

[4]R. R. Wilson, Nucl. Instr. & Methods 1, 101 (1957).

[5]K. Berkelman, J. M. Cassels, D. N. Olson, and R. R. Wilson, in Proceedings of the Tenth Annual International Rochester Conference on High-Energy Physics, 1960, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), p. 757.

[6]In this experiment it was impossible to reach higher W and θ values, because the angle between the incident beam direction and the pion spectrometer could not be made less than 20° because of geometrical limitations.

[7]When the final pion energy is narrowly fixed as in this experiment, the radiative correction to the electroproduction cross section is very similar to the correction one applies to elastic e-p scattering. The normalized cross sections are then very insensitive to radiative effects. We are indebted to D. R. Yennie for helpful suggestions on this point.

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[9]L. N. Hand, Phys. Rev. 129, 1834 (1963). References to earlier work are given in this paper.

[10]G. F. Chew, F. E. Low, M. L. Goldberger, and Y. Nambu, Phys. Rev. 106, 1345 (1957).

[11]S. Fubini et al. do not explicitely include F_π in their formulation; they assume it to be unity, the normalization value at $k^2=0$. To include the F_π dependence, one multiplies F_π into each term in the amplitude which does not already include a nucleon form factor. The resulting expression is still gauge invariant for any value of F_π. In evaluating the cross sections we have omitted the small resonance terms arising from the 33-state projections of the pion-pole amplitude. This has generally been done in recent analyses of photoproduction; see, for example, G. Höhler and W. Schmidt, Ann. Phys. (N.Y.) 28, 34 (1964).

[12]Likewise, the predicted $k^2\to 0$ limit of T is too large compared with the π^0 180° photoproduction data at $W=1210$ MeV.

[13]It is somewhat reassuring, however, to note that the theoretical $k^2\to 0$ limit of T agrees fairly well with the π^+ 0° photoproduction data at both values of W.

[14]The target pions in this experiment are off the mass shell by an amount $\Delta-\mu^2=-2.7\mu^2$ and $-1.9\mu^2$ at $W=1210$ and $W=1313$ MeV, respectively; and one is led to ask whether the F_π measured in electroproduction is the same as the F_π of a free pion. The $(\Delta-\mu^2)$-dependent correction to the pion-pole term (form factor and propagator) may in fact turn out to be quite small, since the generalized Ward identity [F. E. Low, Phys. Rev. 110, 974 (1958)] can be used to show, first, that the correction must vanish in the low-k^2 limit, and second, that the correction vanishes for any k^2 provided that the pion-charge structure can be accounted for by diagrams in which a single particle (a vector meson) couples the photon to the pion (D. R. Yennie, private communication).

[15]R. R. Wilson and J. S. Levinger, Ann. Rev. Nucl. Sci. 14, 135 (1964).

PARAMETERS OF THE $K_0\bar{K}_0$ SYSTEM*

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When no conservation law is assumed—P, C, CP, T, or CPT—Sachs[1] has shown that the time dependence of a K_0-$\bar{K}_0$ mixed state can still be described with the help of a short-lived state $|K_S\rangle$ and a long-lived state $|K_L\rangle$:

$$|K_S\rangle=p_S|K_0\rangle+q_S|\bar{K}_0\rangle,$$

$$|K_L\rangle=p_L|K_0\rangle-q_L|\bar{K}_0\rangle. \quad (1)$$

Several authors[1-4] have set limits for the parameters p_S, q_S, p_L and q_L under different assumptions concerning the decay processes—either CPT invariance, the $\Delta I=\frac{1}{2}$ rule, or excluding the possibility of accidental cancellation. To our present knowledge, it has not been pointed out yet how well all these parameters are known from already performed experiments, from the properties of unitarity, and from an assumption of negligible C violations in strong