ysis by Gordon,[12] prompted by this experiment, shows that the Minkowski momentum is a pseudomomentum that gives the correct value of the observed forces on a liquid surface or a metal vane[5] and yet does not invalidate the true Abraham momentum.

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Electroproduction of ρ and φ Mesons*

J. T. Dakin, G. J. Feldman, W. L. Lakin,† F. Martin, M. L. Perl, E. W. Petraske,‡ and W. T. Toner§
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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We report measurements of ρ^0 and φ electroproduction at 19.5 GeV in a wide-aperture spectrometer which detected the scattered electron and the decay products of the vector mesons. As $|q^2|$ increases, the ρ mass spectrum shape changes, the momentum-transfer distribution broadens, and the ratio of the ρ cross section to the total cross section decreases. The ratio of longitudinally to transversely polarized ρ^0 mesons is $0.45^{+0.15}_{-0.10}$ at $|q^2| = m_\rho^2$, and the interference between longitudinal and transverse amplitudes is almost maximal. The relative φ-meson cross section also decreases as $|q^2|$ increases.

Many photoproduction processes can be understood by assuming that the photon couples directly to vector-meson states. By studying vector-meson electroproduction we seek to determine how this coupling evolves as the photon becomes spacelike and its polarization has longitudinal as well as transverse components. We report here a measurement of ρ electroproduction which combines high virtual-photon energies and the ability to study ρ production and decay angular correlations.[1]

The ρ electroproduction reaction

$$ep \to ep\pi^+\pi^- \tag{1}$$

can be regarded as an inelastic electron scatter ($e \to e\gamma^*$) followed by the virtual photoproduction of a ρ ($\gamma^* p \to \rho p$) followed by the ρ decay ($\rho \to \pi^+\pi^-$). Quantities describing the electron scatter are q^2, the photon mass squared; ϵ, the photon polarization; and s, the c.m. energy squared in the $\gamma^* p$ collision. The ρ production is characterized by t', the four-momentum transfer squared to the proton less its smallest possible value ($t_{\rm min}$); and ϕ_e, the azimuthal angle between the electron scatter plane and the ρ production plane. The final $\pi^+\pi^-$ system is described by its invariant mass $m_{\pi\pi}$; ϕ, the azimuthal angle between the ρ production plane and the ρ decay plane; and θ, the ρ decay polar angle. The angle $\psi \equiv \phi_e + \phi$ is the angle between the electron scatter plane and the ρ decay plane in the limit $t' \to 0$. We use the same angle conventions as Dieterle.[2]

The experimental apparatus, which has been described elsewhere,[3] consisted of a 19.5-GeV/c electron beam incident on a hydrogen target followed by a large-aperture magnetic spectrometer. The optical chambers were triggered by an array of shower counters each time an incident electron scattered more than 30 mrad from the beam with an energy $E' \gtrsim 4$ GeV.

All of the film was measured by a flying-spot digitizer and selected samples were also measured by a conventional manual system. Scattered electrons were identified as tracks whose momenta matched the appropriate shower counter pulse heights. All other tracks were assumed to be hadrons. The number of electrons in each q^2-s interval was corrected for geometric efficiency, measuring losses, hadron contamination (0 to 7%), and radiative effects (10 to 48%).[4] The result was the total number of virtual-photon interactions in the data in that q^2-s interval, or effectively the γ^*p total cross section, $\sigma_{tot}(q^2, s)$.

Each event with three or more tracks was measured up to three times by the manual system to see whether it contained an $e, \pi^+\pi^-$ combination consistent with a one-constraint fit with Reaction (1). The missing- (proton) mass-squared interval allowed was from 0.2 to 1.6 GeV^2. There were 238 "ρ" events surviving this process in the kinematic range $-0.25 > q^2 > -2.00$ (GeV/c)^2, $10 < s < 30$ GeV^2, $0 > t' > -0.7$ (GeV/c)^2, and $0.6 < m_{\pi\pi} < 0.9$ GeV. These events were divided into three q^2 bins whose average properties were $q^2 = -0.36, -0.70, -1.27$; $s = 22.6, 19.6, 19.8$; $\epsilon = 0.67, 0.74, 0.72$; and $t_{min} = -0.008, -0.015, -0.033$.

The events in each bin were fitted by a maximum-likelihood technique with the form

$$\frac{d\sigma_\rho(q^2, s)}{dt' d\phi_e \, d\psi \, d(\cos\theta)} = \sigma_{tot}(q^2, s)\frac{\sigma_\rho}{\sigma_{tot}} \, b e^{bt'} W(\phi_e, \psi, \theta). \quad (2)$$

The fitting function contained the normalization $\sigma_{tot}(q^2, s)$ determined by counting electrons and the detailed dependence of the geometric efficiency on the independent variables q^2, s, t, ϕ_e, ψ, and $\cos\theta$. The output from the fit included the ratio σ_ρ/σ_{tot}, the slope parameter b, and parameters from the angular correlation term, W, to be described later.

The normalized cross section, σ_ρ/σ_{tot}, was corrected for elastic ρ losses due to radiation (24%),[5] the missing-mass cut (9%), the $m_{\pi\pi}$ cut (29%), scanning and measuring losses (10%), and numerous small instrumental effects (13%). A correction was also made for the number of $\pi\pi$ events in the $m_{\pi\pi}$ interval used which were not elastic ρ events (5%). The overall systematic uncertainty in σ_ρ/σ_{tot} is estimated to be 16%. The error bars indicated in the figures represent statistical errors only.

Figure 1 shows the invariant mass distribution of all pion pairs consistent with the hypothesis of Reaction (1). The di-pion mass spectrum is dominated by the ρ^0 meson with little or no background. Some of the events with di-pion mass

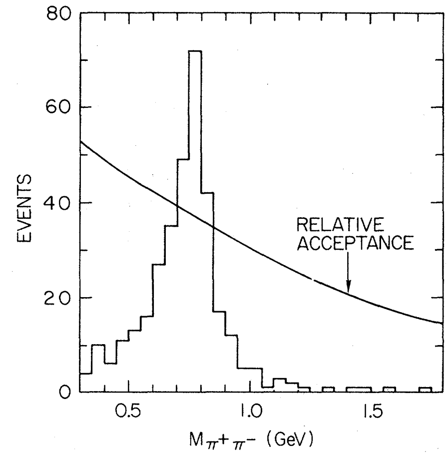

FIG. 1. Di-pion mass spectrum for all events in which the missing mass is consistent with that of a proton. The curve represents the relative acceptance averaged over all other variables.

less than 0.4 GeV are consistent with the hypothesis

$$\gamma^*p \to \varphi p, \quad \varphi \to K^+K^-. \quad (3)$$

These events will be discussed later.

To study possible changes in the ρ^0 mass spectrum as a function of q^2, we fitted the data in the range $0.44 < m_{\pi\pi} < 1.04$ GeV in each q^2 bin by the form

$$d\sigma/dm_{\pi\pi} = (m_\rho^2/m_{\pi\pi}^2)^{n/2} B(m_{\pi\pi}), \quad (4)$$

where $B(m_{\pi\pi})$ is a relativistic p-wave Breit-Wigner shape[6] with the mass (=0.77 GeV) and width (=0.145 GeV) fixed at photoproduction values.[7] The photoproduction data were fitted in an identical manner. All of the data were fitted well by Eq. (4). When a flat background term was added to Eq. (4), the fit values of n did not change appreciably and backgrounds selected by the fits were between 0 and 5%. The fit values of n are shown in Fig. 2(a). The ρ mass shape appears to become more "normal" as $|q^2|$ increases. This effect was predicted by a diffraction-dissociation model,[8] but the prescription given by that model,

$$\left(\frac{m_\rho^2}{m_{\pi\pi}^2}\right)^{n/2} \to \left(\frac{m_\rho^2 - q^2}{m_{\pi\pi}^2 - q^2}\right)^{n/2}, \quad (5)$$

provides a more drastic change in the ρ mass spectrum for $|q^2| \lesssim m_\rho^2$ than is indicated by the data.

We fitted t' distributions by the form $e^{bt'}$ in the range $0 > t' > -0.7$ (GeV/c)^2 in each of the q^2 bins.

The results of these fits are shown in Fig. 2(b) along with photoproduction results,[7,9] which have been analyzed in the same manner as our data. The parameter b appears to decrease with increasing $|q^2|$. We have attempted to determine the t' distribution separately for longitudinally and transversely polarized ρ^0 mesons and have found no significant difference between them.

The complete angular distributions for the production and decay of vector mesons have been given by Dieterle.[2] We have studied the angular correlations in the data for evidence for helicity-nonconserving amplitudes and have failed to find any at the 10% level. Thus we have assumed that s-channel helicity conservation holds in electroproduction, as it does in photoproduction, and have fitted the data with the angular distribution

$$W(\theta,\psi)=\frac{3}{8\pi^2(1+\epsilon R)}\{\epsilon R\cos^2\theta+\tfrac{1}{2}\sin^2\theta(1+\epsilon\cos2\psi)-[\epsilon R(1+\epsilon)/2]^{1/2}\cos\delta\sin2\theta\cos\psi\}, \tag{6}$$

where R is the production ratio of longitudinally to transversely polarized ρ^0 mesons and δ is the phase angle between the longitudinal and transverse amplitudes. The results of the fits for R and $\cos\delta$ are given in Figs. 2(c) and 2(d). For a purely diffractive production process $\cos\delta$ should be unity.

Sakurai and Schildknecht have tried to understand inelastic electron-proton scattering in terms of the production of vector-meson states[10] [we refer to this as the vector-meson–dominance (VMD) model]. We have fitted R with the form suggested by this model,

$$R=-\xi^2q^2/m_\rho^{\,2}. \tag{7}$$

The data are adequately described by this fit with $\xi^2=0.45^{+0.15}_{-0.10}$; however this value of ξ^2 does not appear to be consistent with the value required by the VMD model to fit inelastic electron scattering results ($\xi^2\approx0.06$). The data are somewhat better described by the *Ansatz* suggested by Eckardt *et al.*,[11]

$$R=-q^2(m_\rho^{\,2}-q^2)^{-1}. \tag{8}$$

Figure 2(e) shows the ratio of the ρ^0 virtual photoproduction cross section to the total virtual photoproduction cross section. Photoproduction cross-section ratios, which were obtained by similar analysis methods, are also shown. The ρ^0 cross section drops faster than the total virtual photoproduction cross section and also faster than the prediction of the VMD model,

$$\left.\frac{d\sigma(q^2)}{dt}\right|_{t=0}=\left.\frac{d\sigma(0)}{dt}\right|_{t=0}\frac{(1-\epsilon\xi^2q^2/m_\rho^{\,2})}{(1-q^2/m_\rho^{\,2})^2}, \tag{9}$$

with $\xi^2=0.45$. We note, however, that the data can be described by the simple form,

$$\sigma_\rho(q^2)=\sigma_\rho(0)\exp(bt_{\min})(1-q^2/m_\rho^{\,2})^{-2}. \tag{10}$$

Both Eqs. (9) and (10) are displayed in Fig. 2(e) in terms of cross-section ratios.

There were six events which satisfied the hypothesis of exclusive φ meson production, Reaction (3). We estimate that the background from electron, muon, and pion pairs was 1 ± 1 events. The average q^2 of the events was -0.6 (GeV/c)^2

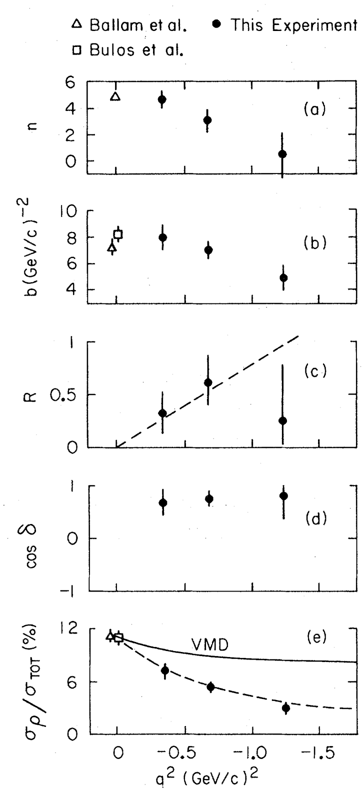

FIG. 2. (a) The parameter n defined in Eq. (4). (b) The parameter b from fits with the form $e^{bt'}$. (c) The ratio of longitudinal to transverse ρ^0 production. The dashed line is the best fit with Eq. (7). (d) Cosine of the longitudinal-transverse phase difference. (e) The ratio of the ρ^0 virtual photoproduction cross section to the total virtual photoproduction cross section. The solid curve represents the prediction of the VMD model, Eq. (9), and the dashed curve represents Eq. (10). Photoproduction data ($q^2=0$) are taken from Refs. 7 and 9.

and the average s was 22.9 GeV^2. The acceptance for φ's was 60% larger than that for ρ^0's; the corrections were similar except for meson mass cut (0%), K decay (42%), and unseen decay modes (104%). The ratio of the φ virtual photoproduction cross section to the total virtual photoproduction cross section is 0.0017 ± 0.0009 compared with 0.0046 ± 0.0006 for photoproduction.[7]

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†Present address: Birmingham Radiation Centre, University of Birmingham, P. O. Box 363, Birmingham B15 2TT, England.

‡Present address: Vanderbilt University, Nashville, Tenn. 37203.

§Present address: Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

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$K_L{}^0 p \to p K_S{}^0$ Backward Scattering from 1.0 to 7.5 GeV/c*

G. W. Brandenburg, W. B. Johnson, D. W. G. S. Leith, J. S. Loos,† G. J. Luste,‡ J. A. J. Matthews, K. Moriyasu,§ W. M. Smart,‖ F. C. Winkelmann,¶ and R. J. Yamartino**

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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Backward scattering in the reaction $K_L{}^0 p \to p K_S{}^0$ is studied in the momentum interval 1.0 to 7.5 GeV/c. Comparison of $K_L{}^0 p \to p K_S{}^0$ and $K^+ p \to p K^+$ backward scattering, where respectively Σ exchange and Λ plus Σ exchange can contribute in the u channel, reveals that

$$\left(\frac{d\sigma}{d\Omega}\right)_{180^\circ} (K_L{}^0 p \to p K_S{}^0) \ll \left(\frac{d\sigma}{d\Omega}\right)_{180^\circ} (K^+ p \to p K^+)$$

above the resonance region. This result provides direct evidence for the dominance of the Λ contribution over the Σ contribution in the $K^+ p \to p K^+$ production amplitude.

In this Letter we present the first measurement of the backward differential cross section for the reaction

$$K_L{}^0 p \to p K_S{}^0 \qquad (1)$$

in the momentum interval 1.0 to 7.5 GeV/c. When combined with previously measured $K^+ p \to p K^+$ cross sections, these data provide a direct comparison of Λ and Σ exchange couplings.

Indirect comparisons of the Λ and Σ couplings have been made using backward $\pi^- p \to \Lambda^0 K^0$ data[1,2] which, like Reaction (1), isolate u-channel Σ ex-