Observation of meson resonances in electroproduction

T. J. Killian,* E. A. Treadwell,[†] L. A. Ahrens,[‡] K. Berkelman, D. G. Cassel, C. T. Day,[§] B. G. Gibbard,[‡] D. J. Harding,[†] D. L. Hartill, J. W. Humphrey,[‡] J. S. Klinger,[†] J. T. Linnemann,[‖] and D. H. White[‡]
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

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We observe an enhancement in the four-pion state $\pi^+\pi^-\pi^+\pi^-$ at 1.8-GeV/c^2 effective mass in electroproduction. Indications of enhancements in the $K^+K^-\pi^+\pi^-$ state are also observed near 1.8, 2.1, and 2.5 GeV/c^2. We compare these observations with others in photoproduction and e^+e^- annihilation.

It is expected that the vector mesons ρ, ω, ϕ will have excited states in the mass region between 1.2 and 2.5 GeV/c^2. There has been evidence in this direction for quite some time, and there has been a great deal of experimental effort devoted to searches for these states. The present understanding derives mainly from the efforts at the ADONE and ACO storage rings.[1,2]

Although it seems clear that there is structure in this mass region, the present data quality leaves some difficulties in interpretation, particularly since any wide resonance is difficult to separate from the phase-space background. We describe here an analysis based on observation of the following two reactions:

$$e+p \to e+p+\pi^+ +\pi^+ +\pi^- +\pi^-, \tag{1}$$

$$e+p \to e+p+K^+ +\pi^+ +K^- +\pi^-. \tag{2}$$

We expect to describe the apparatus in detail elsewhere,[3] and here we emphasize the features that are especially relevant to the present analysis. The experiment is shown schematically in Fig. 1. The magnet field was generated by a conventional 96D40 wide-aperture magnet. Normal operating field at the center was 0.8 T. An electron beam of 11.5 GeV was extracted from the Cornell electron synchrotron and focused on a 7.5-cm-long hydrogen target. Events were triggered by the observation of an electron of energy greater than 2 GeV scattered through an angle greater than 100 mrad.

The final-state particles were detected in the multiwire proportional chambers shown in Fig. 1. On each side of the center line seven chambers measured horizontal coordinates (bend direction), six measured vertical coordinates, and four measured coordinates at 30° to the undeflected beam line; this layout with the chambers parallel to one another simplified the analysis. The seventh chamber was placed perpendicular to the beam so as to use all of the magnetic-field volume for momentum analysis. There were a total of approximately 20 000 sensitive wires in the system.

The scattered electron was detected in a lead-scintillator sandwich counter. Subsequent study revealed that the pion contamination in the trigger was negligible.[4] The momenta of the particles were measured by reconstructing the tracks

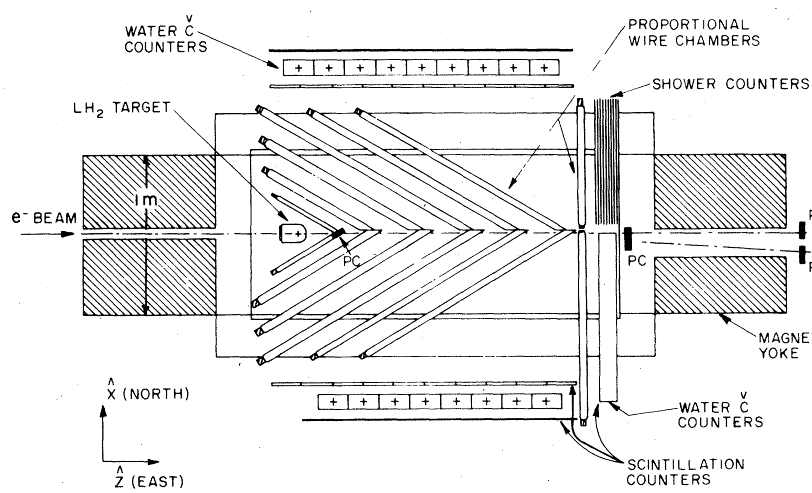

FIG. 1. Plan view of the apparatus.

through the magnetic field. The momentum resolution was limited only by the wire spacing of the proportional chambers and is given approximately by the relation $\sigma_p/p^2 \approx 0.02$ (GeV/c)$^{-1}$.

Approximately 10^8 triggers were read out during the total life of the experiment. Of these, 2×10^7 were considered as having likely electron candidates by the on-line PDP-11, and were written to the raw-data tape for off-line track finding and geometric reconstruction. In the data sample reported here, events were selected in which there were six visible tracks and overall charge zero. There were 3×10^3 events in this class. The large number of tracks resulted typically in low momenta and thus the momentum resolution after geometric reconstruction tended to be quite good. However, these low momenta made this sample relatively difficult to reconstruct by producing tracks which frequently crossed over one another in the view parallel to the magnetic field. Chamber strikes could easily be misassigned where two tracks passed close to one another.

These strikes were a small fraction of the total (on the order of 4 out of 70 to 80 total, as revealed by hand-scanning), so they did not affect the momentum measurement very much. They did, however, introduce non-Gaussian errors into the geometric fit, resulting in a large population in the tail of the χ^2 distribution. Accordingly, we used a relatively loose acceptance criterion on the geometric track reconstruction, $\chi_0^2 < 31$/degree of freedom, and relied on the kinematic fitting for the selection of a clean sample.

The reactions (1) and (2) were next tested for three-momentum balance by making a three-constraint (3C) kinematic fit. Events were accepted if the χ^2 from the 3C fit was less than 100. 1500 candidates passed this cut, and were subsequently subjected to a 4C fit. The electron was positively identified by the shower counter, leaving 18 possible strangeness-conserving hypotheses, which were tested in turn. Most events (~1000) did not have convergent fits for any of the hypotheses; the remaining ones converged in usually three or four cases. For these events, we calculated the χ^2 probabilities, p_1 and p_2 for the two best fits, and plotted the "polarization" between them: $(p_1-p_2)/(p_1+p_2)$. This distribution is shown in Fig. 2. We made a cut at 0.5—events above this cut were passed as unambiguous.

Finally, events were required to have a vertex in the hydrogen target near the known beam trajectory, although this cut had negligible effect. We ended up with 500 events in the final sample. The c.m. energy of the virtual-photon–proton system was constrained to be above 2.7 GeV. The average Q^2, or virtual-photon "mass," was approximately 1.0 GeV^2 for this sample.

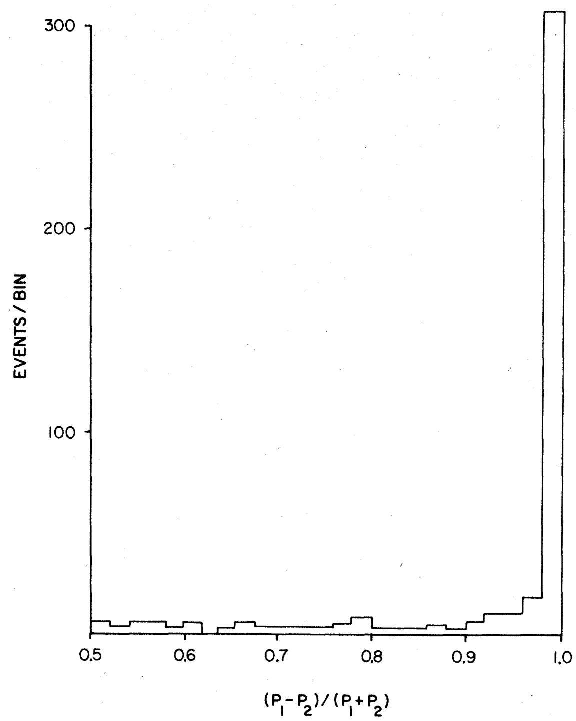

FIG. 2. The ratio $(P_1-P_2)/(P_1+P_2)$ for the probabilities of the most likely and next most likely hypothesis for each event.

The mass of the 4π system was calculated. For those events for which the interpretation was unambiguously reaction 1, the distribution is plotted in Fig. 3. This distribution was fitted to a smoothly varying background and a Breit-Wigner function whose mass and width were allowed to float. The best fit results are $m = 1.78$ GeV/c^2 and $\Gamma = 0.10$ GeV/c^2. The smoothly varying background was constructed from a phase-space distribution limited in transverse momentum. The fit function is also shown in Fig. 3. The experimental mass resolution at this mass is 0.020 GeV/c^2 as calculated from a detailed Monte Carlo simulation of the apparatus and as verified by a comparison with other reactions,[5] notably

$$e + p \to e + \phi + p . \tag{3}$$

An invariant mass distribution for K^+K^- combinations in this reaction is shown in Fig. 4. The Monte Carlo study confirmed our expectation that the efficiency with which these events were selected by the track-finding programs and subsequently filtered as described above should vary smoothly over the available mass range; however, it is difficult to estimate the overall magnitude of the efficiency. We are thus only able to offer an approximate normalization. The 34 events that are in the peak correspond to a virtual-

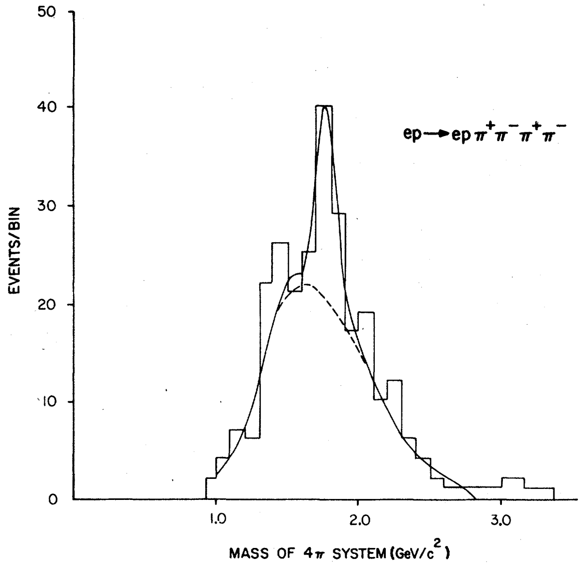

FIG. 3. The invariant mass of the four-pion system for unambiguous events satisfying the hypothesis $ep \rightarrow ep\ \pi^+\pi^-\pi^+\pi^-$. The lines in the figure are a phase-space function and a Breit-Wigner distribution with $m = 1.78$ GeV/c^2 and $\Gamma = 0.10$ GeV/c^2.

photon-proton cross section of 0.2 μb. The cross section for the process

$$\gamma_v + p \rightarrow \rho_0 + p \tag{4}$$

is about 1.5 μb in the same range of W and Q^2.

For the events in Fig. 3 we have plotted in Fig. 5 the mass of all neutral combinations $\pi^+\pi^-$. A

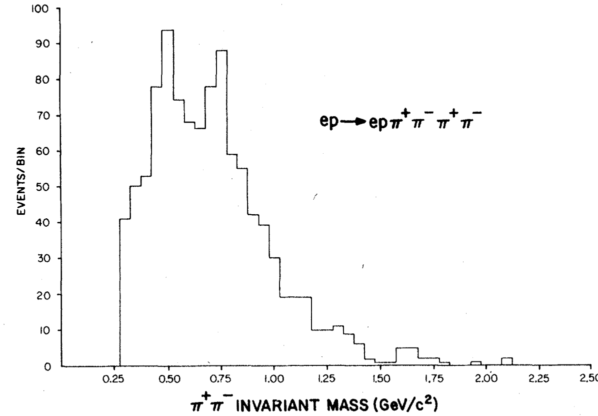

FIG. 5. The invariant mass of the $\pi^+\pi^-$ pairs in the events of Fig. 3. Each event is plotted four times. The ρ^0 appears at the accepted mass.

signal at the mass of the ρ^0 is visible above a combinatorial background. The magnitude of this signal is such that about 30% of all four-pion events contain a ρ^0. The statistical quality of this sample together with the combinatorial problem makes it impossible to be quantitative in estimating the fraction of the 1.78-GeV/c^2 state that decays to $\rho\pi\pi$; however, the number of ρ's is compatible with $\rho\pi\pi$ as a dominant decay mode.

In Fig. 6 we plot a t distribution for the protons in the 4π sample (the ordinate is actually $t - t_{\min}$). We find a slope of 1.0 (GeV/c)$^{-2}$. The bulk of the cross section is clearly nonperipheral. We note that for ρ^0 production at this value of Q^2, the slope is 5 (GeV/c)$^{-2}$,[6] while ρ photoproduction slopes range between about 5.5 and 7 (GeV/c)$^{-2}$.[7]

In Fig. 7 we show the mass distribution of the $K^+K^-\pi^+\pi^-$ combination for the unambiguous events of reaction 2. Here the statistical strength of the data is less satisfactory, but it is nevertheless clear that a phase-space model is inadequate.

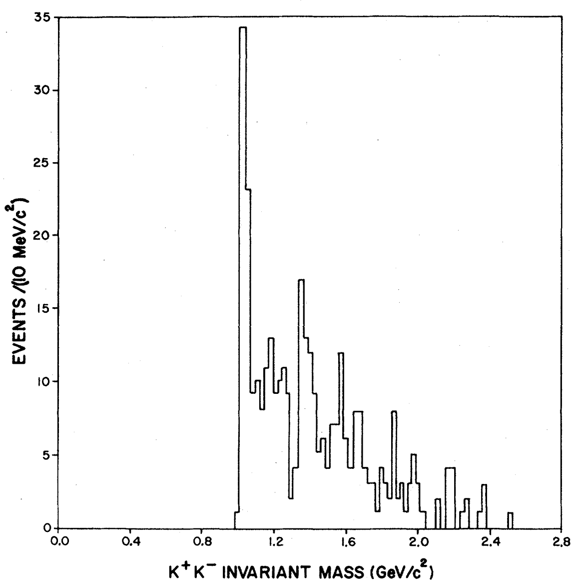

FIG. 4. The invariant mass of the K^+K^- pairs in events from the reaction $ep \rightarrow ep\ K^+K^-$. An enhancement at the mass of the ϕ (1.019 GeV/c^2) is apparent, the width is 0.020 GeV/c^2.

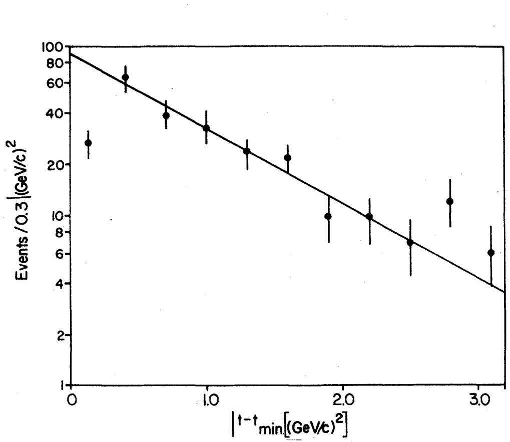

FIG. 6. Number of 4π events vs ($t - t_{\min}$); the straight line fit has a slope of 1.0 (GeV/c)$^{-2}$.

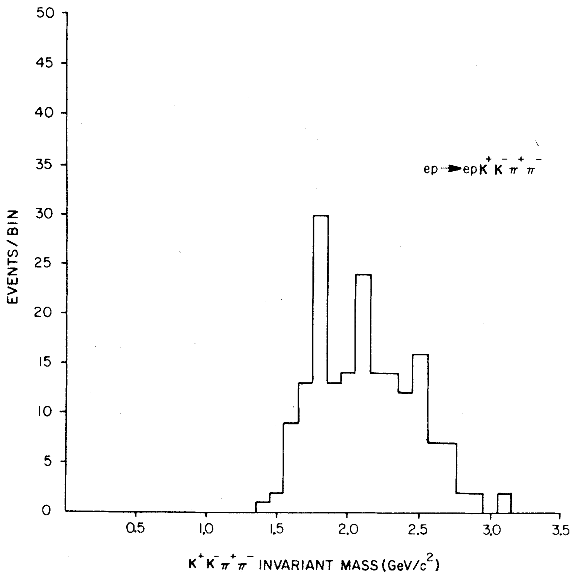

FIG. 7. The invariant mass of the $K^+K^-\pi^+\pi^-$ system for unambiguous events satisfying the hypothesis $ep \to ep\ K^+K^-\pi^+\pi^-$.

A simple polynomial fit results in a χ^2 of 40 for 16 degrees of freedom. If we treat the data in a manner similar to that used for reaction (1), we obtain the results shown in Fig. 8, which also displays the data on an expanded scale. The error bars are statistical. We have fitted for the amplitudes, masses, and widths of the three resonances, in addition to a polynomial background. The χ^2 is 6.6 for 9 degrees of freedom; each peak is a 3-standard-deviation effect.

The masses and widths determined are shown

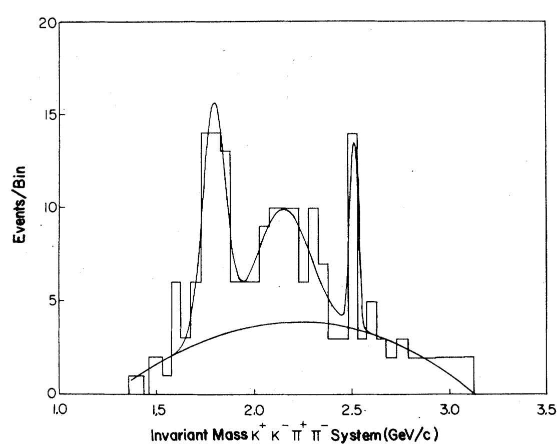

FIG. 8. The events of Fig. 7. on an expanded mass scale showing the results of a maximum-likelihood fit.

TABLE I. Resonances in $ep \to epK^+\pi^+K^-\pi^-$.

	Mass (GeV/c^2)	Width (GeV/c^2)
1	1.80 ± 0.02	0.06 ± 0.02
2	2.15 ± 0.04	0.14 ± 0.04
3	2.51 ± 0.02	0.01 ± 0.03

in Table I. While we feel that we have clear evidence for structure in the $2K2\pi$ channel, we do not feel that the existence of these three states is established by these data alone. Further details of the analysis presented here are contained in Ref. 8.

The ACO group reports the observation of two even-G-parity resonances, one at 1.53 ± 0.02 GeV/c^2 with a width of 0.20 ± 0.07 GeV/c^2 and at 1.69 ± 0.014 GeV/c^2 with a width of 0.18 ± 0.09 GeV/c^2. A small contribution from the state at 1540 could easily be incorporated in a fit to our data. The state at 1690 appears not to correspond to the one reported here, but upon closer examination the two data samples seem to be reconcilable, principally through a reformation of the background used in the experimental fits. An enhancement is observed at 1.78 GeV/c^2 by Cosme *et al.*,[9] but these authors conclude that this state is odd G parity and thus not identifiable with the enhancement reported here. The ADONE events in which no photons are observed do not contain marked structure near 1.80 GeV/c^2; for the events in which photons are observed in the ADONE data, structure is reported but this is interpreted as a state decaying into an odd number of pions.

The state near 1800 MeV in the $K^+K^-\pi^+\pi^-$ data in Fig. 7 appears to be at the same mass, though it may be narrower than that in the $\pi^+\pi^-\pi^+\pi^-$ data in Fig. 3. A state in the $\pi^+\pi^-\pi^+\pi^-\pi^0$ system has been at 1.82 GeV/c^2 by the MEA group,[10] although this assignment of decay particles to the enhancement is not unique in their experiment.

In conclusion, we report the observation of a state decaying into $\pi^+\pi^-\pi^+\pi^-$ at a mass of 1.78 GeV/c^2 and a width of 0.10 GeV/c^2. We also report indications of states at 1.80, 2.10, 2.50 GeV/c^2 in the $K^+K^-\pi^+\pi^-$ system, and an increase of strange-particle production with Q^2.

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*Present address: EP Division, CERN, 1211 Geneva 23, Switzerland.

† Address: Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.

‡Address: Brookhaven National Laboratory, Upton, New York 11973.

§ Address: Lawrence Berkeley Laboratory, Berkeley, California 94702.

‖Present address: Rockefeller University Group, CERN, 1211 Geneva 23, Switzerland.

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