states or new production thresholds, or both.

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[1]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[2]A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975).

[3]V. Lüth *et al.*, Phys. Rev. Lett. 35, 1124 (1975).

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5]J. D. Jackson and D. L. Scharre, Nucl. Instrum. Methods 128, 13 (1975).

[6]J. Kogut and L. Susskind, Phys. Rev. D 12, 2821 (1975); E. Eichten *et al.*, Cornell University Report No. CLNS-323, 1975 (to be published).

Observation of Two Strangeness-One Axial-Vector Mesons*

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We present a partial-wave analysis of the $K^\pm\pi^+\pi^-$ system in $K^\pm p \to K^\pm\pi^+\pi^- p$ at 13 GeV. Evidence is given for the existence of two $J^P = 1^+$ mesons: one at ~1300 MeV ($\Gamma \sim 200$ MeV) coupling principally to ρK and the other at ~1400 MeV ($\Gamma \sim 160$ MeV) coupling principally to $K^*\pi$.

An outstanding problem of meson spectroscopy is the lack of positive identification of the axial-vector mesons other than the B meson.[1,2] The quark model predicts two octets of such states, the A_1 octet with $J^{PC} = 1^{++}$ and the B octet with $J^{PC} = 1^{+-}$. In this paper evidence is given for the existence of two strange axial-vector mesons, Q_1 and Q_2, with masses of ~1300 and ~1400 MeV, respectively. The evidence comes from a three-body partial-wave analysis of data from a spectrometer experiment studying the reactions $K^\pm p \to K^\pm\pi^+\pi^- p$ at 13 GeV.

Past searches for Q mesons in these reactions have been hampered by both experimental and interpretive problems. Previous partial-wave analyses[3-5] of $K\pi\pi$ data have revealed no structure characteristic of resonance production, namely, comparatively narrow peaks in the mass spectrum accompanied by large phase variation. Statistics have limited these analyses to 100-MeV mass bins. The broad enhancements which have been observed in the 1^+ $K^*\pi$ system[3-5] may be qualitatively understood within the context of "Deck" models.[6]

The present experiment was performed at Stanford Linear Accelerator Center using 13-GeV rf-separated $K^\pm$ beams incident on a 1-m hydrogen target. The spectrometer[7] used to detect the $K\pi\pi$ system consisted of nine magnetostrictive read-out wire spark chambers and a dipole magnet with a 17.6-kG-m field integral. The secondary particles were identified in a multicell pressurized Cherenkov counter oriented to detect preferentially the beam-charge K and π. The counter was filled with Freon 12 at 1.65 atm and gave K/π identification between 2.6 and 9.25 GeV. The data sample includes events in which the beam-charge K and π were identified (~50%) together with events with only the K or the π positively identified (~25% each). Events for the present analysis are selected by requiring that the missing mass recoiling against the $K\pi\pi$ system lie in the range $0.74 < MM < 1.10$ GeV. The background within this interval is less than 5%. In the $K\pi\pi$ mass interval $1.0 < m(K\pi\pi) < 1.6$ GeV, there are 72 000 $K^+\pi^+\pi^-$ events and 56 000 $K^-\pi^+\pi^-$ events. For the much larger sample of $K^\pm \to \pi^\pm\pi^+\pi^-$ beam decays, used for apparatus efficiency studies and relative normalization checks, the 3π invariant-mass resolution is 10 MeV full width at half-maximum.

At a given $K\pi\pi$ mass m and momentum transfer t (or $t' = t - t_{\min}$), the $K\pi\pi$ system is defined by five variables, $\omega = (\alpha, \beta, \gamma, s_{K\pi}, s_{\pi\pi})$. The Euler angles α, β, and γ describe the orientation of the $K\pi\pi$ decay plane coordinate system with respect to a production coordinate system which is taken to be the t-channel system.[8,9] The Dalitz-plot variables, $s_{K\pi}$ and $s_{\pi\pi}$, define the orientation of particles within the decay plane. The experimental data are not corrected for the spectrometer acceptance directly, but rather a model is made for the reaction, the effects of the spectrometer are introduced, and the result is compared with the experimental data through a maximum-likelihood technique. Acceptance here includes not only the geometrical acceptance of the spectrometer but also the effects of K/π identification criteria, resolution, apparatus efficiencies, secondary-particle absorption, and the cuts applied to the data. In general the apparatus provides good acceptance in the full range of ω.[9]

The isobar model[8,9] is used to describe the decay of the $K\pi\pi$ system. Each partial wave is described by the quantum numbers J^PM^η Iso(L), where J^P is the $K\pi\pi$ spin and parity, M is the magnetic substate, η is the exchange naturality, Iso denotes the isobar (K^*,ρ,κ,ϵ), and L is the orbital angular momentum between the isobar and the remaining π or K. The isobars are in turn described by measured s- and p-wave $K\pi$- and $\pi\pi$-scattering phase shifts.

The differential cross section at a given $K\pi\pi$ mass m and t' is

$$\frac{d^7\sigma}{dm\,dt'\,d\omega}=\sum_\eta[|\sum_i N_i{}^\eta X_i{}^\eta(\omega)|^2+|\sum_i F_i{}^\eta X_i{}^\eta(\omega)|^2],$$

where i runs over all necessary waves and $X_i{}^\eta(\omega)$ is the decay amplitude.[8,9] $N_i{}^\eta$ and $F_i{}^\eta$ may be identified with nucleon helicity-nonflip and -flip amplitudes only up to a unitary transformation which leaves the differential cross section unchanged.[9,10] Results are given for the acceptance corrected cross section of a wave and its phase, $\varphi_{\rm rel}$, as *measured relative to* $1^+0^+ K^*\pi$.

The helicity nonflip waves used in this analysis were 0^-0^+, 1^+0^+, and 1^+1^+ coupling to each of the four isobar channels in the lowest allowed L; $2^+1^+ K^*\pi$ (D); and $3^+0^+ K^*\pi$ (D) above 1.43 GeV. The helicity flip waves were 1^+0^+, $1^+1^+ \rho K$ (S), and $1^+0^+ \epsilon K$ (P). The only η odd wave was 2^+0^- $K^*\pi$ (D). This wave set was arrived at by an iterative procedure in which many other waves were studied using the K^+ data in all mass bins. Only those waves giving significant increases in likelihood were retained.[9]

The results presented here correspond to an analysis of the data with ~3000 events in each mass interval for $|t'|<0.3$ GeV^2. In each bin, searches for the parameters $N_i{}^\eta$ and $F_i{}^\eta$ were made for the K^+ and K^- data independently. In

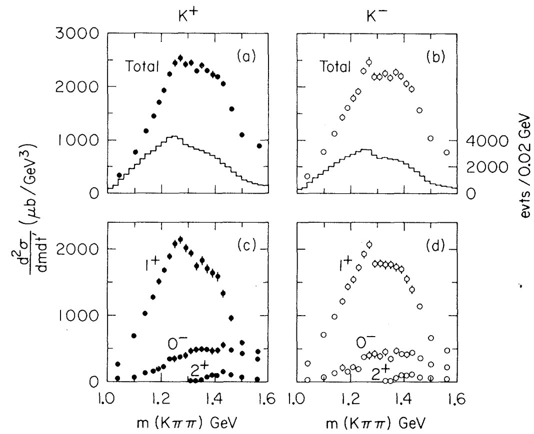

FIG. 1. Observed and corrected mass spectrum and principal total J^P contributions. The right-hand scale refers only to the observed spectrum; the left-hand scale, only to the corrected spectrum.

general, unique values for these parameters were found, with the exception that for the K^- data in the range $1.14 \leq m(K\pi\pi) \leq 1.25$ GeV, a restricted continuum of values was found. None of the conclusions made below is seriously affected by this ambiguity. In particular, the total cross section and total J^P contributions are in no way affected.

The observed mass distributions are shown in Figs. 1(a) and 1(b); a significant break is seen at ~1.28 GeV. The points give the corrected cross section obtained by summing the contributions of all the waves present. In Figs. 1(c) and 1(d), the contributions of each J^P state are shown. Spin and parity 1^+ dominates the reaction over most of this mass region and accounts for the gross structure observed. The 0^- contribution becomes important at higher masses. In the region of the $K^*(1420)$, a small but distinct 2^+ signal is seen. It is only ~5% of the total cross section at this mass.

The intensity and relative phase of the principal $K^*\pi$ and ρK waves with $J^P=1^+, 2^+$ and $\eta=+1$ are shown in Figs. 2 and 3. For regions of $m(K\pi\pi)$ where the intensity of a wave is small ($\lesssim 20$ μb/GeV^3) and susceptible to fluctuations in measurement, its phase information in unreliable. The line shape of the $2^+1^+ K^*\pi$ wave shown in Figs. 2(e) and 2(f) is well described by nominal mass and width parameters for the $K^*(1420)$.[2] Furthermore, the observed $K^*(1420)$ cross section is in excellent agreement with that expected from experiments detecting the $(K\pi)^\pm$ decay mode.[2,9]

The $1^+ K^*\pi$ waves are shown in Figs. 2(a)–2(d). There are significant differences between the K^+

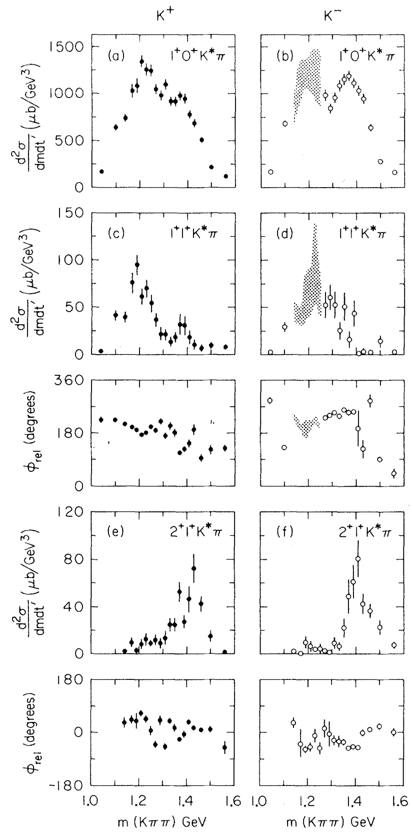

FIG. 2. Mass dependence of the 1^+0^+, 1^+1^+, and 2^+1^+ $K^*\pi$ waves. The phase, $\varphi_{\rm rel}$, is measured with respect to 1^+0^+ $K^*\pi$. The shaded area indicates the range of ambiguity.

and K^- data. In the $1^+0^+ K^*\pi$ waves, there are clearly two peaks in the K^- data but only a peak-shoulder structure in the K^+ data. The higher mass peak in the K^- data occurs at ~1380 MeV, well beyond the ambiguous region. As seen in Figs. 2(e) and 2(f), there is little phase variation ($\lesssim 45°$) of the $2^+1^+ K^*\pi$ wave in the vicinity of 1420 MeV. The $1^+1^+ K^*\pi$ waves are significant in the 1200-MeV region, but are $\lesssim 10\%$ of the 1^+0^+ $K^*\pi$ waves in intensity, indicative of t-channel helicity conservation for the $1^+ K^*\pi$ waves.

In the $1^+ \rho K$ system (Fig. 3), peaks of width ~200 MeV are observed in all waves at ~1280 MeV. Furthermore, there are pronounced phase variations: a forward motion of ~70° for 1.20 $< m(K\pi\pi) <$ 1.35 GeV and a backward motion of ~50° for 1.35 $< m(K\pi\pi) <$ 1.45 GeV. The ratio of $1^+1^+ \rho K$ to 1^+0^+ ρK ($\sim\frac{1}{3}$) is certainly *not* indicative of t-channel helicity conservation.[4,5] The measured coherence between the ρK and 1^+0^+ $K^*\pi$ waves is ~0.75 for the entire $K\pi\pi$ mass range.[9]

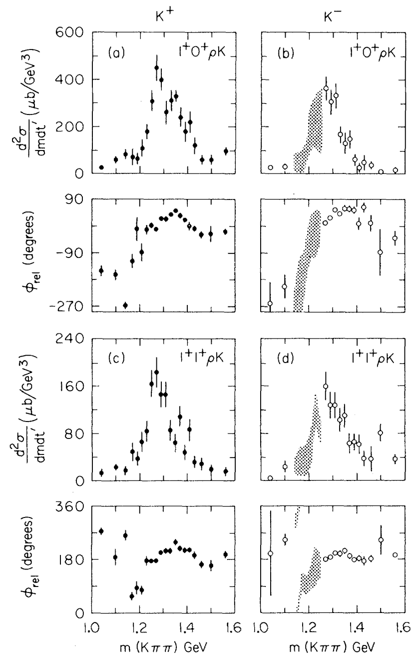

FIG. 3. Mass dependence of the 1^+0^+ and 1^+1^+ ρK waves. The phase, $\varphi_{\rm rel}$, is measured with respect to 1^+0^+ $K^*\pi$. The shaded area indicates the range of ambiguity.

These features may be explained qualitatively in terms of two 1^+ resonances, Q_1 at ~1300 MeV coupling principally to ρK and Q_2 at ~1400 MeV coupling principally to $K^*\pi$, and a "Deck" background peaking at ~1200 MeV in the $1^+ K^*\pi$ system. The evidence for such an interpretation is summarized as follows.

(a) There are comparatively narrow peaks in the partial-wave mass spectra. Q_1 has a width of ~200 MeV and Q_2, a width of ~160 MeV. Such narrow peaks are not expected to result from "Deck" mechanisms.

(b) The large forward phase variation of the ρK waves would correspond to a resonance if the reference wave were approximately constant in phase. This would be the case if a significant background were present in $1^+ K^*\pi$ and/or the Q_1 coupling to $K^*\pi$ were small.

(c) The suppressed phase variation of $K^*(1420)$ relative to 1^+0^+ $K^*\pi$ would indicate that this reference wave is also executing a Breit-Wigner phase variation in the region of 1400 MeV. In addition, if Q_2 couples weakly to ρK, a backward phase motion for the $1^+ \rho K$ waves would then be expected.

(d) The residual low-mass peaks in $1^+ K^*\pi$ may be associated with a "Deck" background. Indeed little phase variation is observed between $1^+ K^*\pi$ waves and the structureless $0^- 0^+ K^*\pi$ wave[9] as expected of "Deck" mechanisms.[6]

The large increase in statistics of the present experiment has allowed a partial-wave analysis to be performed in much finer mass intervals, revealing distinct structure heretofore undetected. In particular, intensity and phase variations with widths $\lesssim 200$ MeV have been observed. These effects may be interpreted as due to the existence of two 1^+ mesons Q_1 and Q_2, in accord with the multiplet structure implied by the quark model. These states would presumably be mixtures of Q_A and Q_B, the octet partners of the A_1 and B.

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[1]R. Eisner, in *Experimental Meson Spectroscopy —1974*, AIP Conference Proceedings No. 21, edited by D. Garelick (American Institute of Physics, New York, 1974).

[2]V. Chaloupka *et al.*, Phys. Lett. 50B, 1 (1974).

[3]Yu. Antipov *et al.*, Nucl. Phys. 86B, 365 (1975).

[4]S. Tovey *et al.*, Nucl Phys. 95B, 109 (1975).

[5]G. Otter *et al.*, Nucl. Phys. 93B, 365 (1975).

[6]E. Berger, in *Proceedings of the Daresbury Conference on Analysis of Three-Particle Phase Shift Analysis and Meson Resonance Production, 1975*, edited by J. Dainton and A. J. G. Hey (Daresbury Nuclear Physics Laboratory, Daresbury, Warrington, Lancashire, England, 1975); G. Ascoli *et al.*, Phys. Rev. D 8, 3894 (1973).

[7]G. Brandenburg *et al.*, to be published.

[8]D. Herndon *et al.*, Phys. Rev. D 11, 3165 (1975).

[9]G. Brandenburg *et al.*, to be published.

[10]This parametrization permits the measurement of spin coherence and the imposition of rank conditions in a manner similar to that of S. U. Chung and T. L. Trueman, Phys. Rev. D 11, 633 (1975).

Production Properties of Q Mesons in $K^{\pm}p \to K^{\pm}\pi^+\pi^- p$ at 13 GeV*

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The momentum transfer (t') dependence of the $J^P = 1^+$ $K^*\pi$ and ρK partial waves in the $K^{\pm}\pi^+\pi^-$ system is presented. The production of the Q_1 meson ($m \sim 1300$ MeV), which has a large ρK decay mode, obeys approximate s-channel helicity conservation. In contrast the production of the Q_2 meson ($m \sim 1400$ MeV), which decays predominantly to $K^*\pi$, satisfies approximate t-channel helicity conservation. Furthermore the $Q_1^{\pm}$ production distributions are virtually identical, whereas the $Q_2^{\pm}$ distributions exhibit a distinct crossover for $|t'| \sim 0.18$ GeV^2.

In the previous Letter,[1] the results of a partial-wave analysis investigating the spin and parity structure of the $K\pi\pi$ system were presented as a function of mass for the reactions

$$K^{\pm}p \to K^{\pm}\pi^+\pi^- p \qquad (1)$$

at 13 GeV. Definite structure was observed in the intensity and phase variation of the 1^+ partial waves and was interpreted as evidence for the existence of the two strange 1^+ Q mesons expected from the quark model. The Q_1 meson at ~ 1300 MeV was observed to have a large ρK decay, while the Q_2 meson at ~ 1400 MeV decays predominantly to $K^*\pi$. In addition, a large low-mass peak in the 1^+ $K^*\pi$ system near 1200 MeV was ascribed to a "Deck" mechanism.

In this Letter the t' dependence of the partial waves associated with these structures in the mass spectrum is presented. The production properties are studied in three regions: Region (I),

$$1.16 < m(K\pi\pi) < 1.28 \text{ GeV},$$