OBSERVATION OF TWO NON-LEADING STRANGENESS-ONE VECTOR MESONS*

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ABSTRACT

We present evidence for the existence of two strange $J^P = 1^-$ mesons; one at $1410 \text{ MeV}/c^2$ coupling principally to $K^*(892)\pi$, and the other at $1790 \text{ MeV}/c^2$ coupling to $K\pi$, $K^*\pi$ and ρK . The data derive from a partial wave analysis of the $\bar{K}^0\pi^+\pi^-$ system produced in the reaction $K^-p \rightarrow \bar{K}^0\pi^+\pi^-n$ at $11 \text{ GeV}/c$. The production mechanism and quark model assignment of each state are discussed. The state at $1410 \text{ MeV}/c^2$ is most naturally understood as the first radial excitation of the $K^*(892)$, and the $1790 \text{ MeV}/c^2$ object can be interpreted as the triplet D wave partner to the $3^- K^*(1780)$.

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One of the most important problems remaining for meson spectroscopy is the understanding of the light quark spectra in the mass region between 1000 and 2000 MeV/c^2 . Though the leading $q\bar{q}$ excitations in this mass region have been rather well understood for some time, the lack of positive identification and measurement of many of the expected non-leading states has important implications; not only for the quark model, but also for the identification of non- $q\bar{q}$ species such as glueballs, which are predicted to lie in this same mass region. Since many of the states overlap substantially and can have the same quantum numbers, the experimental situation is very confusing. Perhaps the cleanest way to study the $q\bar{q}$ spectrum is with the strange meson systems, where the flavorless glueball states do not occur.

Most light quark potential models predict that at least two strange $J^P = 1^-(K^{*'})$ mesons should exist in the 1000 to 2000 MeV/c^2 mass region. One is expected to be a radial excitation of the $K^*(892)$, while the other would be the triplet partner of the $K^*(1780)$. In this paper, evidence is given for the existence of two strange vector mesons with masses of 1410 MeV/c^2 and 1790 MeV/c^2 , which can be associated with these expected states. This evidence comes from a partial wave analysis of the $\bar{K}^0\pi^+\pi^-$ system in the reaction

$$K^-p \rightarrow \bar{K}^0\pi^+\pi^-n \quad (1)$$

at 11 GeV/c .¹

Previous evidence for possible $K^{*'}$ states has come from both the elastic $K^-\pi^+$ channel and the inelastic 3-body $K\pi\pi$ channels. In the elastic channel,² resonant behaviour was observed in the P wave around 1700 MeV/c^2 , and is most simply interpreted as a single resonance with a substantial background amplitude. In the inelastic channels, the $K^-\pi^+\pi^-$ analysis with the highest statistics³ did not require any substantial 1^- amplitude. However, this channel is dominated by very large diffractively produced waves and is, as a result, less sensitive to a small 1^- amplitude. On the other hand, the $\bar{K}^0\pi^+\pi^-$ analyses have generally suffered from either poor statistics or low acceptance, particularly above 1600 MeV/c^2 . However, in the highest statistics analyses,⁴⁻⁶ there is evidence for a 1^- resonance around 1450 MeV/c^2 with hints of possible structure at higher mass.

The present data are obtained from a 1000 events/ μb exposure of the LASS

spectrometer. The design of the spectrometer, coupled with the choice of experimental trigger, gives rather uniform acceptance over the entire solid angle. Details of the experiment and the spectrometer are given elsewhere.^{1,2} The final data sample consists of 11,149 events in the $\bar{K}^0\pi^+\pi^-$ invariant mass region below 2300 MeV/c^2 and the momentum transfer region ($|t'| < 1.0 (GeV/c)^2$); the low t' data sample ($|t'| < 0.3 (GeV/c)^2$) contains 7,636 events.

The three-body isobar model⁷ is used to describe the decay of the $\bar{K}^0\pi^+\pi^-$ system. The data are fit to a set of partial wave amplitudes, where each partial wave is specified by the quantum numbers $J^P M^\eta isobar L$ where J^P is the $\bar{K}^0\pi^+\pi^-$ spin-parity, M is the magnetic substate, η is the exchange naturality, *isobar* denotes the two-body isobar ($\kappa, K^*(892), K^*(1430), \epsilon, \rho, f$) and L is the orbital angular momentum between the isobar and the remaining π^+ or $\bar{K}^0$. The isobars are described by parametrisations of the measured S wave $K\pi$ and $\pi\pi$ phase shifts for the κ and ϵ respectively, and relativistic Breit-Wigner resonances for the remaining isobars. Results are given in terms of the acceptance-corrected number of events at production for each wave, and the phase of each wave relative to a reference wave whose imaginary component has been fixed to zero.

The wave set used to obtain the final amplitudes was arrived at by a well-defined iterative procedure which is described in detail in reference 1. Only waves which significantly improved the likelihood were retained. Any remaining differences in wave sets in adjacent mass bins were reconciled by examining the significance of each wave in those mass bins and by requiring continuous behaviour. In general, this procedure gave unique values for the wave solutions everywhere below a mass of 1800 MeV/c^2 , except in the region between 1300 and 1600 MeV/c^2 , where a two-fold ambiguity was resolved by requiring that the 2^+ amplitudes give a consistent description of the $K^*(1430)$.

The corrected mass distribution is shown in figure 1(a). The most prominent structure is the bump around 1400 MeV/c^2 , which is normally associated with the leading $2^+ K^*(1430)$. There is also a broad bump around 1800 MeV/c^2 , which could be attributed to the leading $3^- K^*(1780)$. However, as shown below, both of these regions have substantial 1^- contributions and, in particular, the 1^- waves are the dominant contributors to the 1800 MeV/c^2 structure in the total cross section.

In figures 1(b)-1(e), the contributions of each of the natural spin-parity states to the total intensity in figure 1(a) are shown. The well-known $2^+ K^*(1430)$ and $3^- K^*(1780)$ are clearly observed, and there is also an indication of the next leading K^* , the $4^+ K^*(2060)$. The $J^P = 1^-$ amplitude has a rather sharp rise, starting at about $1300 \text{ MeV}/c^2$, up to a plateau in the 1400 to $1600 \text{ MeV}/c^2$ region. It then shows a dramatic peak centered at about $1750 \text{ MeV}/c^2$. The contribution of this amplitude to the total cross section is very large. It is by far the largest contributing wave in the 1700 to $1800 \text{ MeV}/c^2$ region, and in the region of the $K^*(1430)$ is about half as large as the dominant 2^+ amplitude.

The intensities and phases of the principal 2^+ , 3^- and 1^- $K^*\pi$ and ρK waves are shown in figures 2 and 3. The phases are measured relative to the $1^-0^- K^*P$ wave. The $2^+0^- K^*D$, $2^+0^- \rho D$ and $2^+1^+ K^*D$ intensities exhibit strong resonant behaviour in the $1430 \text{ MeV}/c^2$ region, which is associated with the production and decay of the $2^+ K^*(1430)$. The $3^-0^- K^*F$ intensity shows clear resonant structure in the region around $1800 \text{ MeV}/c^2$ which is attributed to the $3^- K^*(1780)$.

The $J^P = 1^-$ intensity in figure 1(b) is due solely to the $1^-0^- K^*P$ and $1^-0^- \rho P$ waves shown in figure 4. The $1^-0^- K^*P$ intensity shows a peak around $1400 \text{ MeV}/c^2$ and drops to about half its maximum value through the 1600 to $1900 \text{ MeV}/c^2$ region. The $2^+0^- K^*D$ phase relative to the $1^-0^- K^*P$ wave shows little variation through the $1400 \text{ MeV}/c^2$ region. Since the $2^+0^- K^*D$ wave is dominated by the resonant behaviour of the $K^*(1430)$, the $1^-0^- K^*P$ absolute phase advances rapidly through the $1400 \text{ MeV}/c^2$ region. The $3^-0^- K^*F$ phase relative to the $1^-0^- K^*P$ wave in the region where the $3^-0^- K^*F$ amplitude is dominated by the $K^*(1780)$ is relatively constant, indicating that the $1^-0^- K^*P$ absolute phase is also advancing in this region. The $1^-0^- \rho P$ intensity starts to grow above $1450 \text{ MeV}/c^2$ and peaks around $1800 \text{ MeV}/c^2$. The $1^-0^- \rho P$ phase relative to the $1^-0^- K^*P$ wave moves backward in the 1500 - $1600 \text{ MeV}/c^2$ region and then remains constant up through $1900 \text{ MeV}/c^2$.

The variation of each wave with t' indicates the nature of the exchange process responsible for the amplitude. The t' dependences of the amplitudes were determined in two $\bar{K}^0 \pi^+ \pi^-$ mass bins; 1350 to $1510 \text{ MeV}/c^2$ and 1710 to $1890 \text{ MeV}/c^2$. Figure 5 shows the t' dependences for the dominant 1^+ , 1^- , 2^+ and 3^- intensities

in the 1430 (solid line) and 1800 (dashed line) MeV/c^2 regions. Simple exponential fits describe the t' dependences well, as shown. The fitted slope parameters are given in table 1. The $1^+0^+ K^*S$ has a flat t' dependence indicating that the amplitude is produced through the exchange of a heavy meson. The slopes of the $1^-0^- \rho P$, $2^+0^- K^*D$ and $3^-0^- K^*F$ are all quite steep which is suggestive of π exchange. On the other hand, the $1^-0^- K^*P$ wave in the 1400 MeV/c^2 region has a very flat slope, showing that it is also produced by heavy meson exchange. The $1^-0^- K^*P$ in the 1800 MeV/c^2 region displays a significantly steeper slope, quite similar to the $1^-0^- \rho P$ indicating that the two 1^- amplitudes are produced in the same way at the higher $\bar{K}^0 \pi^+ \pi^-$ mass.

The partial wave analysis of the $K^- \pi^+$ system reported in reference 2 throws additional light on the nature of the 1^- amplitudes, since the production of the $K^- \pi^+$ final state is dominated by π -exchange. The $K^- \pi^+$ P wave amplitude is very small in the 1400 MeV/c^2 but displays a relatively large resonant amplitude around 1700 MeV/c^2 .

These features can be explained qualitatively in terms of two $K^{*'}$ resonances: a $K^{*'}(1410)$ coupling principally to $K^*(892)\pi$, and a $K^{*'}(1790)$ which couples to $K^*(892)\pi$, ρK and $K\pi$. The lack of any measurable coupling of the $K^{*'}(1410)$ to the $K\pi$ system explains the flatter t' dependence of its production amplitude.

The consistency of this model was tested by performing a simultaneous fit to the $2^+0^- K^*D$, $3^-0^- K^*F$, $1^-0^- K^*P$ and $1^-0^- \rho P$ intensities and phases. A Breit-Wigner lineshape⁸ was used to model the resonant contributions in these four waves. The resonance parameters of the $2^+0^- K^*D$ amplitude were fixed to a mass of 1433 MeV/c^2 and a width of 131 MeV/c^2 and the resonance parameters of the $3^-0^- K^*F$ amplitude were fixed to a mass of 1790 MeV/c^2 and a width of 138 MeV/c^2 , as determined in reference 1. The lineshapes predicted by these parameters are shown in figures 2 and 3. The 1^- waves were parametrised by two relativistic Breit-Wigners where one resonance contributed to only the $1^-0^- K^*P$ amplitude while the second was coupled to both waves. Polynomial backgrounds for each wave were included in the fit.

The fitted parameters for the 1^- resonances are shown in table 2. The quoted errors are the statistical and systematic uncertainties respectively, where the latter is a measure of the variation in the parameter when different background parametrisations were assumed. The $\rho K / K^* \pi$ branching ratio for the $K^{*'}(1790)$ was determined from the results of the fit described above. The $\rho K / K \pi$ and $K \pi / K^* \pi$ branching ratios for this state were determined by fitting the elastic $K \pi$ P wave amplitude² above $1400 \text{ MeV}/c^2$ to the resonance parameters of the $1790 \text{ MeV}/c^2$ state given in table 2. The limits on the $\rho K / K^* \pi$ and $K \pi / K^* \pi$ branching ratios for the $K^{*'}(1410)$ at the 95% confidence level are also given in the table. The fitted relative phases of the $2^+ 0^- K^* D$ and $3^- 0^- K^* F$ amplitudes are represented by the curves in figures 2 and 3. The curves in figure 4 are the fitted $1^- 0^- K^* P$ and $1^- 0^- \rho P$ amplitudes. The fit reproduced all the features of the measured amplitudes, in particular the relative phases of the four waves.

The states observed in this analysis (as given in Table 2) have a straightforward interpretation in the naive quark model. In particular, two $J^P = 1^-$ states are expected, one being the radial excitation of the S wave triplet $q\bar{q}$ system and the other the D wave triplet state. The $1410 \text{ MeV}/c^2$ object is associated with the S wave radial excitation, and the $1790 \text{ MeV}/c^2$ object with the D wave on the basis of the smallness of typical $L \bullet S$ mass splittings and the mass systematics of the charmonium system. Within this scheme, the lack of significant coupling of the $K^{*'}(1410)$ to the elastic channel is a consequence of the presence of a node in the radial wave function.⁹⁻¹⁰

Two implications of this assignment are that the other members of the first radially-excited vector nonet (ρ' , ω' , ϕ') should lie in the $1250\text{-}1550 \text{ MeV}/c^2$ region, and that they should couple only weakly to the elastic channels. There are observations of a $\rho'(1250)$ with these characteristics in the literature,¹¹⁻¹² though its present status is rather poor. There is no clear observation of the required ω' or ϕ' , but if they preferentially decay into high multiplicity states they would be difficult to observe. A clear observation of any of these states would corroborate the assignment preferred here.

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8. The lineshape of the n th resonance decaying into the j th isobar is given by

$$\frac{d\sigma_n^j}{dM} = N \left[\frac{\sqrt{M M_n \Gamma_n^j}}{M^2 - M_n^2 - i M_n \Gamma_n^{tot}} \right]^2.$$

N is a normalization constant, M is the three-meson invariant mass, and M_n is the resonant mass. The energy-dependent partial width Γ_n^j is parametrised as

$$\Gamma_n^j = \frac{(\gamma_n^j)^2 BF_{L_n^j}(Q^j)}{M_n BF_{L_n^j}(Q_n^j)} \left(\frac{Q^j}{M} \right),$$

where Q^j and Q_n^j are the magnitudes of the 3-momenta of the bachelor meson evaluated in the 3-meson center of mass for masses M and M_n , respectively. The angular momentum eigenstate of the isobar and bachelor system is specified by L_n^j . $BF_{L_n^j}(Q)$ is a barrier factor which behaves as $Q^{2L_n^j}$ at threshold and approaches a constant as $Q \rightarrow \infty$. γ_n^j is a constant which is proportional to the partial width of the resonance. The total width of the resonance Γ_n^{tot} is approximated by a constant independent of Q_n and M .

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TABLE CAPTIONS

1. The exponential slopes of the dominant waves in the 1350-1510 and 1710-1890 MeV/c^2 mass bins.
2. The fitted resonance parameters of the two 1^- states.

TABLE 1: Exponential Slopes of the Major Waves

Wave	Slope $(GeV/c)^{-2}$	
	1350-1510 MeV/c^2	1710-1890 MeV/c^2
$1^+0^+ K^*S$	-3.2 ± 0.5	
$1^-0^- K^*P$	-2.1 ± 0.4	-5.6 ± 0.7
$1^-0^- \rho P$		-8.2 ± 0.9
$2^+0^- K^*D$	-11.5 ± 2.0	
$2^+0^- \rho D$	-8.9 ± 2.1	
$3^-0^- K^*F$		-11.8 ± 3.7

TABLE 2: Resonance Parameters of the $J^P = 1^-$ States

	$K^{*'}(1410)$	$K^{*'}(1790)$
Mass (MeV/c^2)	$1412 \pm 9 \pm 2$	$1786 \pm 4 \pm 8$
Width (MeV/c^2)	$196 \pm 18 \pm 12$	$195 \pm 15 \pm 16$
BR($\rho K / K^* \pi$)	$<.17$ (95% c.l.)	3.4 ± 1.3
BR($\rho K / K \pi$)		1.2 ± 0.4
BR($K \pi / K^* \pi$)	$<.16$ (95% c.l.)	2.8 ± 1.1

FIGURE CAPTIONS

1. Figure 1(a) shows the acceptance-corrected number of events observed as a function of $\bar{K}^0\pi^+\pi^-n$ mass for the interval $|t'| < 0.3 \text{ (GeV/c)}^2$. The natural parity contributions to the total intensity are shown in figures 1(b) through 1(e) for $|t'| < 0.3 \text{ (GeV/c)}^2$.
2. The intensities and relative phases of the $2^+0^- K^*D$ and $2^+0^- \rho D$ waves. The intensity is expressed in events per 20 MeV/c^2 . The curves on the 2^+ intensities are the result of a fit to the lineshapes described in reference 1. The curve on the $2^+0^- K^*D$ relative phase is from the fit to the $J^P = 1^-$ waves described in the text.
3. The intensities and relative phases of the $2^+1^+ K^*D$ and $3^-0^- K^*F$ waves. The intensity is expressed in events per 20 MeV/c^2 . The curves on the lineshapes are from the fits done in reference 1. The curve on the $3^-0^- K^*F$ relative phase is from the fit described in the text.
4. The intensities and relative phases of the $1^-0^- K^*P$ and $1^-0^- \rho P$ amplitudes. The intensity is expressed in events per 20 MeV/c^2 . The $1^-0^- K^*P$ amplitude is used as a reference wave in the partial wave analysis; the phases of the other $\eta -$ waves are measured relative to it. The curves are the result of the fit described in the text.
5. The t' dependences of the largest waves in two mass bins, $1350\text{-}1510 \text{ MeV/c}^2$ (solid points and lines) and $1710\text{-}1890 \text{ MeV/c}^2$ (open points and dashed lines). The fitted exponential distributions are displayed for each wave.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5