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EVIDENCE FOR TWO $J^P = 2^-$ STRANGE MESON STATES IN THE $K_2(1770)$ REGION*

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ABSTRACT

Evidence is presented for two $J^P = 2^-$ strange mesons; one at ~ 1.77 GeV/c^2 and the other at ~ 1.82 GeV/c^2. These states have been observed in a partial wave analysis of the $K\omega$ system in the reaction $K^-p \to K^-\pi^+\pi^-\pi^0 p$ where the strange mesons decay into $K^-\omega$ and the ω then decays to $\pi^+\pi^-\pi^0$. The data set contains $\sim 10^5$ $K\omega p$ events at 11 GeV/c taken by the LASS spectrometer at SLAC.

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Introduction

Although evidence for the quark model is very strong, the correct $q\bar{q}$ quark model assignments of all the known mesons are not completely clear, and conversely, there are several low-mass (≤ 2 GeV/c^2) $q\bar{q}$ states for which there are no experimentally detected candidates. Specifically, in the suggested assignments of the Particle Data Group [1], there is considerable controversy over the assignment of several of the light non-strange mesons. This is particularly true for the 0^{++} multiplet, where there appear to be too many candidate states, and in the D-wave $J^P = 2^-$ sector there is no $q\bar{q}$ combination with good candidates for both singlet and triplet 2^- states. This is true even for the strange meson sector, which is the best understood $q\bar{q}$ system. Even though the number of strange meson states which have been observed is quite large [2], with orbitally excited states up to 5^- and with a significant number of triplet and radially excited candidates, the expected level structure is only complete for the S-wave ($L = 0$) and P-wave ($L = 1$) ground states. In fact it is only for the ground state P-wave sector that both singlet and triplet states are fully understood. Although a strange meson state of $J^P = 2^-$, $K_2(1770)$, has been observed in several experiments [3], no experiment has been able to resolve the singlet and triplet states. If these states were observed, the D-wave multiplet would be complete, and this would considerably sharpen comparison of the experimental data with models of the level structure [4], particularly as they concern spin-dependent forces.

In this paper, we present the results of a high-statistics study of the $K\omega$ system in the $K_2(1770)$ region. The data were obtained in the reaction

$$K^- p \to K^- \pi^+ \pi^- \pi^0 p \tag{1}$$

at 11 GeV/c using the Large Aperture Superconducting Solenoid (LASS) spectrometer at SLAC, which is described in detail elsewhere [5]. Since the LASS spectrometer was not equipped with a photon detector, the π^0 in the final state is not detected directly, but its presence is inferred by assigning the π^0 mass to the the missing momentum vector in a kinematic fit, and then observing a strong ω signal in the resulting $\pi^+\pi^-\pi^0$ effective mass distribution. The sensitivity of the experiment is 4.1 events/nb, and the $K^-\omega p$ sample obtained ($\sim 10^5$ events) is at least 25 times larger than that obtained in any previous experiment. The acceptance of LASS for reaction (1) is nearly uniform over almost the full 4π solid angle.

Event selection and analysis

Initially, events with four charged tracks at the primary vertex and with zero net charge are selected. The following requirements are then imposed: (a) for at least one charged track mass assignment permutation, the missing mass squared (MM^2) recoiling against $K^-\pi^+\pi^-p$ must satisfy $|\mathrm{MM}^2| < 0.3$ $(\mathrm{GeV/c}^2)^2$; (b) with the assumption that the missing neutral system consists of a single π^0, the effective mass of the three pion system for at least one of the surviving mass permutations must satisfy $\mathrm{m}_{3\pi} \leq 1.1$ GeV/c^2. Each acceptable permutation is then subjected to geometric and kinematic fits. The fitting algorithm is described in detail elsewhere [6]. To distinguish reaction (1) from the background process,

$$K^-p \rightarrow K^-\pi^+\pi^-p \qquad (2)$$

a four-constraint (4C) fit to reaction (2) is performed, and events are removed if any mass permutation satisfies this fit with confidence level $\geq 10^{-10}$. The events removed by this requirement exhibit only a very small ω signal in the $\pi^+\pi^-\pi^0$ effective mass distribution when interpreted as reaction (1). For the surviving events, a one-constraint (1C) fit to reaction (1) is performed and only those events yielding a fit with confidence level $\geq 10^{-2}$ are accepted. To further purify the data sample, particle identification checks using dE/dx, time-of-flight, and Cherenkov counter information are made, and only those hypotheses consistent with all such information are retained. The four-momentum transfer squared between the target and recoil protons ($t' = |t_{p\rightarrow p}| - |t_{p\rightarrow p}|_{min}$) is restricted to the range $0.1 \leq t' \leq 2.0$ $(\mathrm{GeV/c})^2$ in order to select events containing a peripherally produced $K\omega$ system; the lower cut-off is necessary since, for $t' \leq 0.08$ $(\mathrm{GeV/c})^2$, the resulting slow proton almost always stops in the target, and is not reconstructed, while for $0.08 \leq t' \leq 0.1$ $(\mathrm{GeV/c})^2$ the reconstruction efficiency increases rapidly and becomes almost constant by $t' = 0.1$ $(\mathrm{GeV/c})^2$.

The surviving events yield 1.86×10^5 $\pi^+\pi^-\pi^0$ combinations in the effective mass interval $0.64 - 0.92$ GeV/c^2. Of these, ~ 93 % are from events which have a unique representation, and ~ 7 % are from events with two acceptable combinations. No events have three or more acceptable combinations. Monte Carlo studies of $K\omega p$ events indicate that the wrong $\pi^+\pi^-\pi^0$ combinations resulting from the selection procedure described above yield an approximately linearly rising background under the ω signal due to correctly interpreted events. The effect of such wrong combination events is correctly taken into account by the background subtraction procedure to be described below.

The $\pi^+\pi^-\pi^0$ mass spectrum shows a clear ω peak (fig. 1) with signal to background ratio about one to one in the signal region ($0.72 - 0.84$ GeV/c^2). It is clear from the corresponding Dalitz plot (fig. 2) that the $K^-\omega$ region of interest in the present analysis ($m_{K\omega} \leq 2.0$ GeV/c^2) overlaps with substantial production of several baryon resonances; for this reason, events with $m_{p\omega} < 2.28$ GeV/c^2 or $m_{pK} < 2.0$ GeV/c^2 are eliminated. The $K^-\pi^+\pi^-\pi^0$ effective mass distribution in the ω region (fig. 3a) shows peaks in the $K\omega$ threshold region and in the $1.7 - 1.8$ GeV/c^2 region. The shaded histogram displays the effect of the m_{pK} and $m_{p\omega}$ cuts. Most of the high mass $K^-\omega$ events lie in these overlap regions and are removed by the cuts.

The analysis, more details of which can be found elsewhere [7], is performed using the joint decay spherical harmonic moments describing the angular distribution of the $K\omega$ system, and the subsequent decay of the ω into 3π's. For a given $K^-\omega$ mass interval, these moments are obtained from the D matrices describing the $K\omega$ and 3π angular distributions according to

$$H(LMlm) = \sum_{i=1}^{N} w_i [D^L_{Mm}(\Omega_1) D^l_{m0}(\Omega_2)]_i \; ; \tag{3}$$

the solid angle $\Omega_1(\theta_1, \phi_1)$ describes the ω direction in the $K\omega$ rest frame with reference to axes defined such that the $\mathbf{z_1}$ axis is along the K^- beam direction and the $\mathbf{y_1}$ axis is normal to the production plane (Gottfried-Jackson frame), and similarly the solid angle $\Omega_2(\theta_2, \phi_2)$ describes the normal vector to the 3π decay plane in the ω rest frame, with the ω direction in the $K\omega$ rest frame as the $\mathbf{z_2}$ axis, and $\mathbf{y_2} = \mathbf{z_1} \times \mathbf{z_2}$.

The weight function w_i in Eq (3) is required in order to perform the subtraction of the background under the ω signal. As the $\pi^+\pi^-\pi^0$ mass spectrum shown in fig. 1 contains a significant background contribution under the ω peak, each moment is background-subtracted by setting w_i to -1 for events in the sideband control regions indicated by the shading ($0.64 - 0.70$ GeV/c^2 and $0.86 - 0.92$ GeV/c^2), to +1 in the signal region, and to 0 elsewhere. In making the background subtraction, it is assumed that that the contributions to the moments $H(LMlm)$ from the ω signal and the non-ω background add incoherently, and that the background is a linear function of $\pi^+\pi^-\pi^0$ mass. In general, this appears to be a good approximation. However, for the $H(0000)$ moment, which represents the $K\omega$ mass spectrum, the background is not well described by a linear function. Therefore, for this moment, the amount of ω signal in each $K^-\pi^+\pi^-\pi^0$ mass bin is measured by fitting the ω lineshape to a double-Gaussian resolution function modelled from a Monte Carlo analysis, combined with a non-ω background term which is parameterized as a quadratic function of $m_{3\pi}$. For each of the other moments, the background in the corresponding $\pi^+\pi^-\pi^0$ mass plot is well-described by a linear function of $m_{3\pi}$ and there is no significant difference between the results of the two methods of extracting the $K\omega$ signal contribution to the $K^-\pi^+\pi^-\pi^0$ intensity.

After background subtraction, the acceptance-corrected moments, H_c, are obtained by multiplying the vector of measured moments by the inverse of the acceptance matrix for the $K\omega$ mass interval in question (the linear algebra method [8]). The resulting acceptance-corrected and background-subtracted $K\omega$ mass spectrum ($H_c(0000)$) is displayed in fig. 3b.

The moments $H(LMlm)$ can be expressed as bilinear combinations of partial wave amplitudes each of which is the product of a production and a decay amplitude [9]. Each partial wave is characterized by a set of quantum numbers* $J^P\Lambda^\eta L'$, where J, P, and Λ are the spin, parity, and helicity of the $K\omega$ system respectively, and L' is the relative orbital angular momentum of the K^- and ω. The variable η is termed naturality [10], since the corresponding amplitude projects, to a good approximation, the contribution to the amplitude in question resulting from the t-channel exchange of a system having that naturality.

The 89 moments with $0 \leq L \leq 6$, $0 \leq M \leq 2$, $l = 0, 2$, and $-2 \leq m \leq 2$ are fitted using as parameters the real and imaginary components of all of the amplitudes having $J^P = 0^-,\ 1^+,\ 1^-,\ 2^+,\ 2^-$, and 3^-. Due to the nonlinearity and complexity of the fitting equations, the partial wave analysis (PWA) solutions are not unique. For each interval of $K^-\omega$ mass, therefore, the PWA fit is tried

*The choice of the quantum numbers follows the convention used in the three-body isobar model (ref. [10]) except that the isobar is fixed to $\omega(782)$.

many times with random parameter initializations; any PWA solution which has a χ^2 exceeding by more than 10 units the minimum value obtained in the interval in question is rejected. In most cases the accepted solutions overlap with one another within one standard deviation. The one standard deviation intervals from all surviving solutions are combined, and the span of the combined intervals is taken as the solution interval. The center of this solution interval is taken as the estimated value of the fitted amplitude, and the half-length of the interval is conservatively assigned as the one standard deviation uncertainty.

The partial wave structure

The low mass $K^-\omega$ region is dominated by 1^+ waves (not shown), while the mass bump around 1.75 GeV/c^2 has spin-parity (J^P) mainly 2^-. The incoherent sum of the intensity contributions of all the $J^P = 2^-$ waves (fig. 4) exhibits a large, broad bump centered at $\sim$ 1.75 GeV/c^2. The much smaller $K^-\omega$ decays of the $K_2^*(1430)$ (not shown) and the $K_3^*(1780)$ are also observed, and have branching fractions which are consistent with the predictions of SU(3) [7]. Figure 5 shows the results of the PWA for the $J^P = 2^-$ and 3^- waves which are significant in the 1.75 GeV/c^2 region. In addition to the bump in the 3^- amplitude corresponding to $K_3^*(1780)$ production, there is significant and rather complicated structure in the 2^- amplitudes. In order to describe these features in terms of the production of resonant states, the following procedure is adopted: first, the 3^- amplitudes are fit to a single Breit-Wigner resonance in order to define a reference wave in the 1.75 GeV/c^2 mass region; then the 2^- and 3^- amplitudes are fit simultaneously with their relative phases and magnitudes as free parameters. Two different descriptions of the $J^P = 2^-$ waves are compared: the first assumes that they result from the production of a single resonance, while the second assumes that they result from the coherent superposition of the Breit-Wigner amplitudes describing two resonances.

The dotted curves in fig. 5 show the fit results corresponding to the first hypothesis. The fitted mass and width of the 2^- resonance are 1728 ± 7 MeV/c^2 and 221 ± 22 MeV/c^2, respectively, and the χ^2 is 128.9 for 116 degrees of freedom. Although the χ^2 per degree of freedom is quite acceptable, the one-resonance fit does not reproduce the behavior of the 2^-1^+F wave at all well; also, the dip at $\sim$ 1.84 GeV/c^2 in the Re(2^-0^+P) and the tail of Re(2^-0^+F) are not well represented by the fit. On the other hand, the fit results corresponding to the two-resonance hypothesis, represented by the solid curves in fig. 5, reproduce all features of the amplitudes very well and provide a significantly better fit to the data, yielding a χ^2 of 70.6 for 110 degrees of freedom. The fitted masses of the two resonances are 1773 ± 8 MeV/c^2 and 1816 ± 13 MeV/c^2, and the corresponding widths are 186 ± 14 MeV/c^2 and 276 ± 35 MeV/c^2, respectively. The fit results are summarized in Table 1.

The χ^2 difference is almost 60 units between the one and two resonance hypotheses. Moreover, since the PWA typically has a number of nearby solutions, the error bars shown and used in the fit tend to be overestimated. It follows that the χ^2 values for these fits are underestimated, so that it is not possible to make a reliable quantitative estimate of the significance of the requirement for a second resonance. Nevertheless, the data clearly prefer the model with two $J^P = 2^-$ resonances.

Conclusions

A partial wave analysis of the $K^-\omega$ system in a high-statistics ($\sim 10^5$) sample of $K^-\omega p$ events provides good evidence for two 2^- strange meson states with masses ~ 1773 and ~ 1816 MeV/c^2. These states are most naturally interpreted in the context of the quark model as the $^1D_2$ and $^3D_2$ ground states. The singlet/triplet assignment of these states cannot be determined, since the strange mesons are not eigenstates of charge conjugation. It follows from this that the observed states may even be mixtures of the singlet and triplet states, as is the case for the $K_1(1270)$ and $K_1(1400)$. Nevertheless, the observation of two 2^- states means that the $q\bar{q}$ ground state D-wave level structure is complete in the strange meson sector, the only such sector for which this is the case.

It is interesting to note that Godfrey and Isgur [4] predict masses of 1780 and 1810 MeV/c^2 for the unmixed $^1D_2$ and $^3D_2$ states respectively, values which are remarkably close to those obtained in the present analysis. Kokowski and Isgur [11] also predict that the pure states are essentially decoupled, with the lower mass state decaying mostly to P-wave and the higher mass state to F-wave. Table 2 shows the coupling strengths obtained from the fit. For the helicity-1 states produced by natural spin-parity exchange, the $K_2(1816)$ couples most strongly to

F-wave (2^-1^+F), which is at least consistent with the Kokowski and Isgur model. Production of $K_2(1773)$ with helicity-1 is so small that little can be said regarding this state. On the other hand, the 2^- states of helicity-0, produced by natural spin-parity exchange, couple preferentially to P-wave $K\omega$ for both the higher ($K_2(1816)$) and the lower ($K_2(1773)$) mass state. It should be noted, however, that the interpretation of the data of Table 2 is complicated by the fact that the quoted cross section value for each state includes the effect of the corresponding production amplitude, which may well differ significantly from state to state.

Acknowledgments

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Table 1: The results of the Breit-Wigner fits to the 2^- waves.

Fit Model	Mass (MeV/c^2)	Width (MeV/c^2)	χ^2/dof.
one 2^- resonance	1728 ± 7	221 ± 22	128.9/116
two 2^- resonances	1773 ± 8	186 ± 14	70.6/110
	1816 ± 13	276 ± 35	

Table 2: The strengths of the two $J^P = 2^-$ strange states, $K_2(1773)$ and $K_2(1816)$, in the partial wave amplitudes. The numbers represent the effective cross section (in μb) of each state contributing to the corresponding partial wave.

wave	$K_2(1773)$ (μb)	$K_2(1816)$ (μb)
2^-0^+P	7.6 ± 1.2	6.4 ± 1.4
2^-0^+F	1.1 ± 0.5	0.2 ± 0.2
2^-1^+P	small, no B-W fit	
2^-1^+F	0 ± 0.02	0.8 ± 0.4

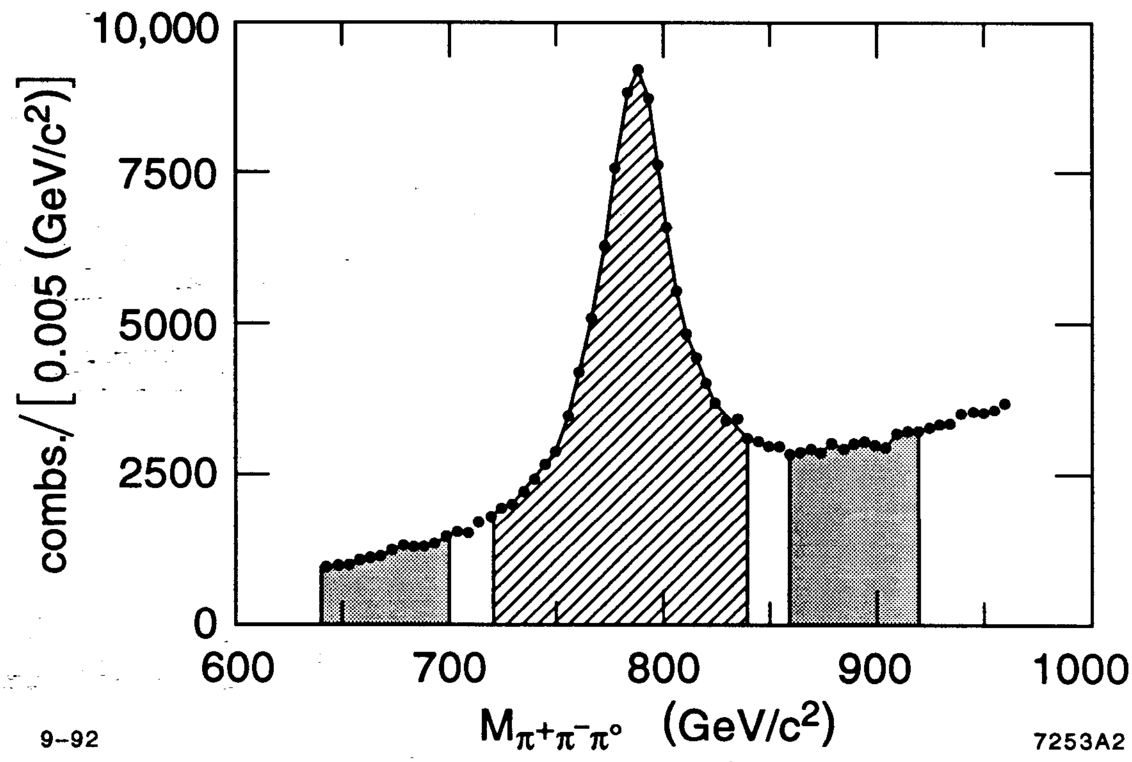

Figure 1: The $\pi^+\pi^-\pi^0$ invariant mass distribution for combinations that pass the confidence level and particle ID cuts, and satisfy $0.1 < t' < 2.0$ $(\mathrm{GeV/c})^2$; the signal region is diagonally-lined while the background control regions are shaded.

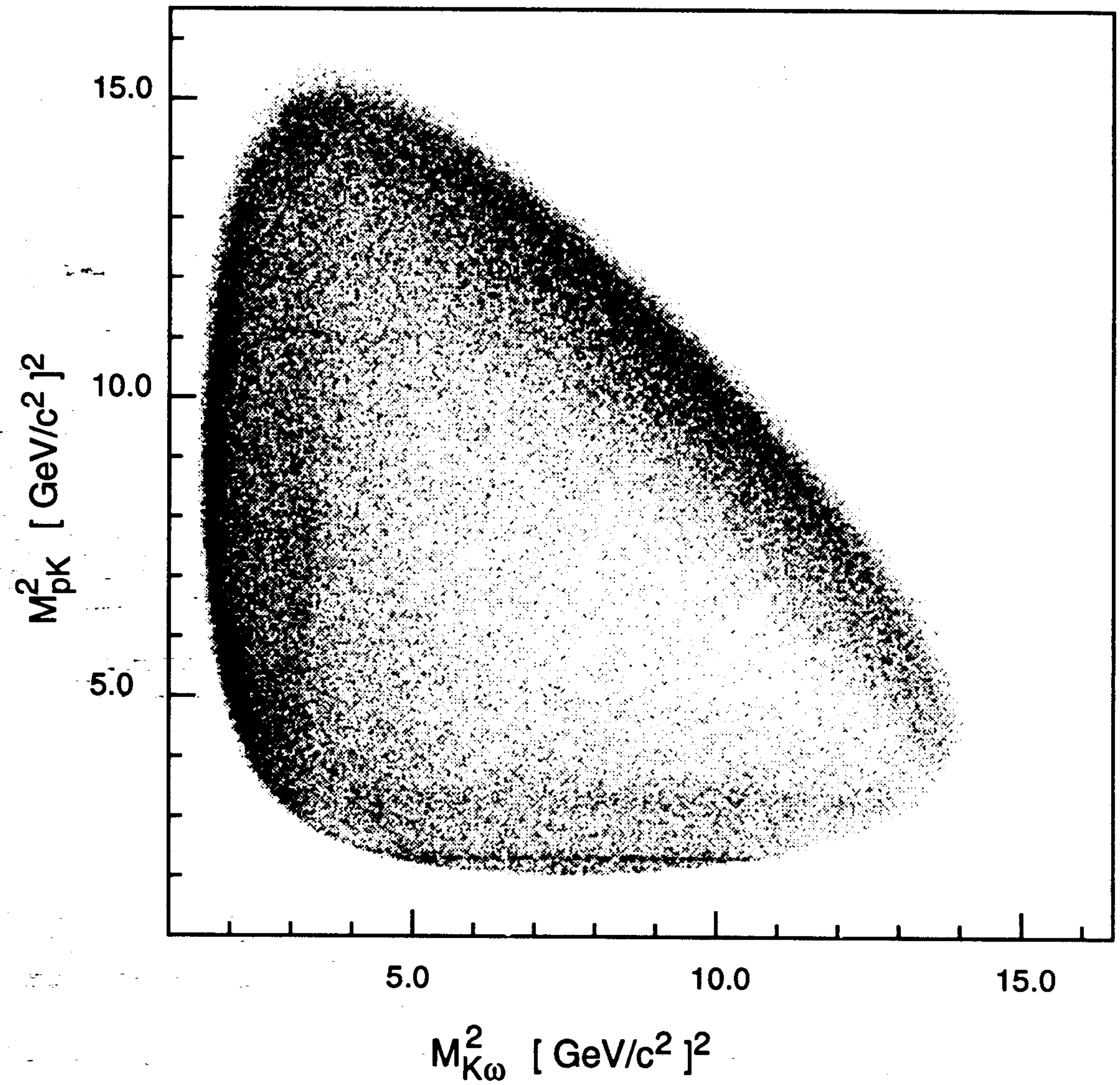

Figure 2: The Dalitz plot for reaction (1) for events with $0.1 \leq t' \leq 2.0$ (GeV/c)^2 and $0.72 < m_{\pi^+\pi^-\pi^0} < 0.84$ GeV/c^2. The production of $\Lambda(1520)$, an additional broad enhancement for $m_{pK} \sim 1.8$ GeV/c^2, and a low-mass enhancement in $m_{p\omega}$ are seen to yield background contributions in the region of $K\omega$ mass considered in the present analysis.

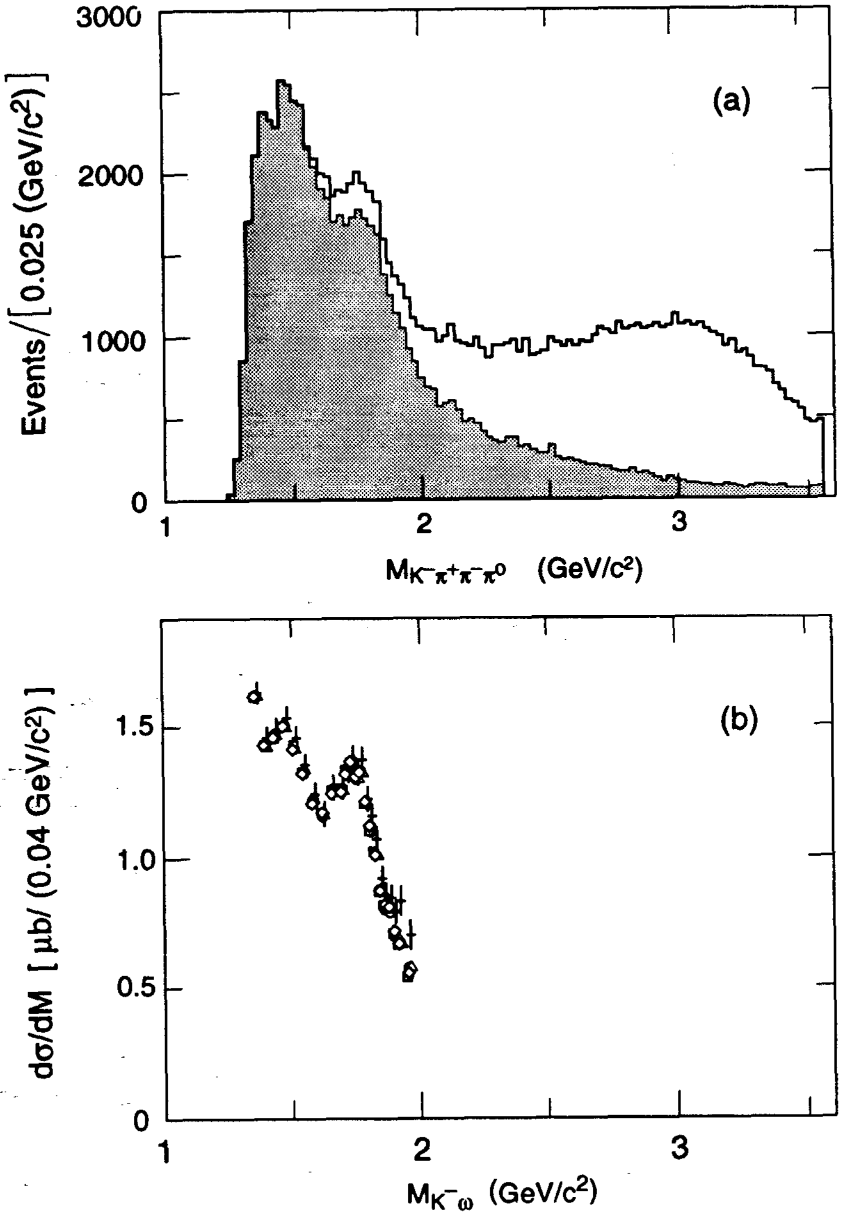

Figure 3: The $K^-\pi^+\pi^-\pi^0$ invariant mass distribution for events with $0.1 < t' < 2.0$ (GeV/c)^2. (a) The unshaded curve contains all events that satisfy $0.72 < m_{\pi^+\pi^-\pi^0} < 0.84$ GeV/c^2 while the shaded portion contains only events with $m_{p\omega} > 2.28$ GeV/c^2 and $m_{pK} > 2.0$ GeV/c^2. (b) The background-subtracted and acceptance-corrected $K\omega$ differential cross section; the points with error bars are the measured values and the points displayed by various symbols are the PWA-fitted values shown for comparison. Corrections have been made for unseen ω decay modes.

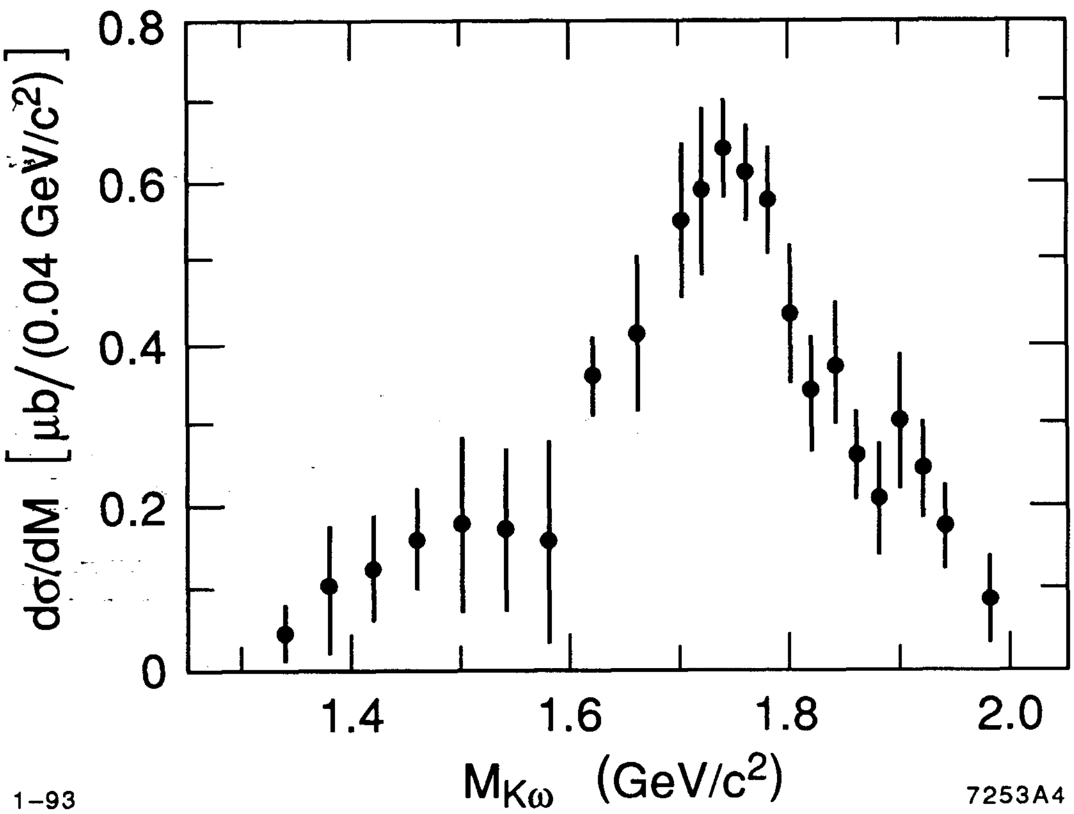

Figure 4: The differential cross section corresponding to the summed intensities of the 2^- waves; corrections have been made for unseen ω decay modes. The integrated cross section for $m_{K\omega} \leq 2.0$ GeV/c^2 is (4.68 ± 0.33) μb.

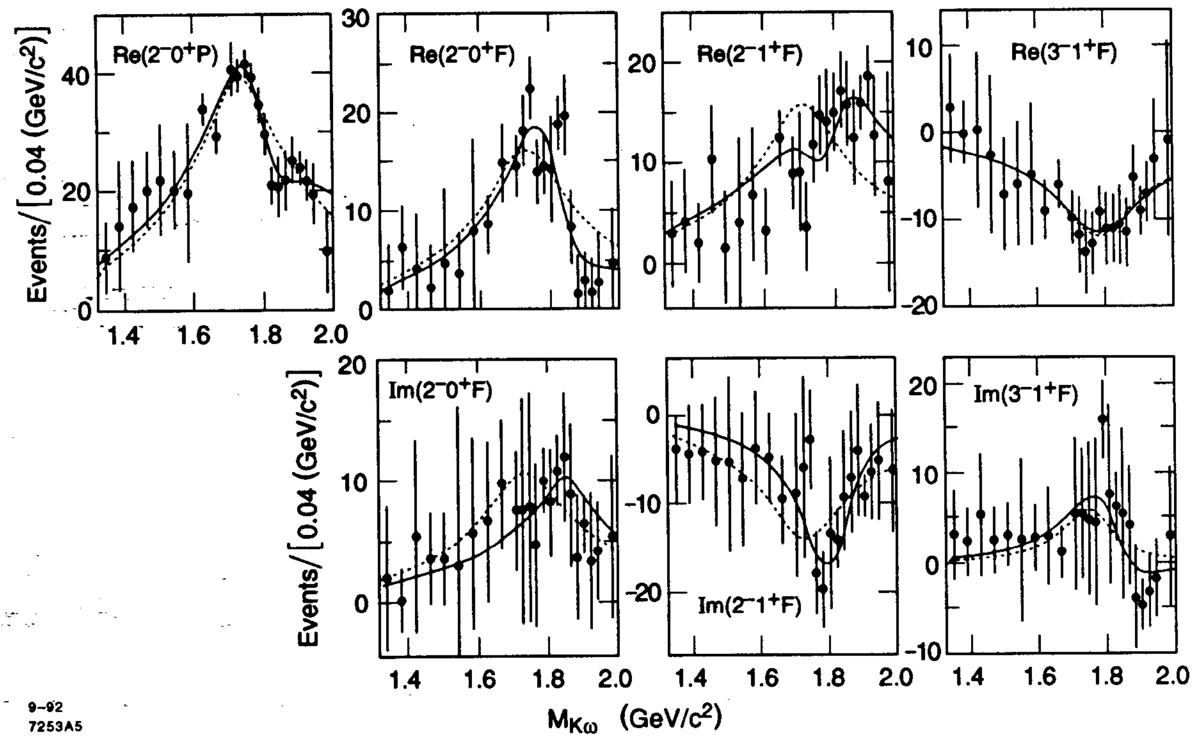

Figure 5: The real and imaginary parts of the $K^-\omega$ $J^P = 2^-$ and 3^- amplitudes produced by t-channel natural parity exchange; the curves show the results of the fits described in the text.