PROPERTIES OF THE f^* MESON*

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In this Letter we present new information concerning the decay modes and the spin and parity (J^P) assignment of the f^* meson.[1] A systematic search for all possible decay modes was carried out, and resulted in (1) direct observation of the K^+K^- mode, (2) a restrictive upper limit for the 2π decay mode, (3) a revision of the K^*K decay rate, (4) a two-standard-deviation indication of an $\eta^0\pi\pi$ decay mode, and (5) an upper limit for $\eta^0\eta^0$ decay. The absence of a K_1K_2 mode establishes that the f^* must be even under charge conjugation, C, and restricts the possible J^P assignments to the values 0^+, 2^+, 4^+, etc. Studies of the $K\bar{K}$ decay angular distributions permit one essentially to rule out 0^+.

The data for this study come from an analysis of K^-p interactions at 4.6- and 5.0 BeV/c incident K^- momenta, using the Brookhaven National Laboratory 80-inch bubble chamber. The exposure had an effective yield of 12 events per microbarn of cross section. The final states[2,3] relevant to a study of the f^* are

$$(\Lambda^0, \Sigma^0)K^0\bar{K}^0, \quad (1)$$

$$(\Lambda^0, \Sigma^0)K^+K^-, \quad (2)$$

$$(\Lambda^0, \Sigma^0)\pi^+\pi^-, \quad (3)$$

$$(\Lambda^0, \Sigma^0)K\bar{K}\pi, \quad (4)$$

$$(\Lambda^0, \Sigma^0)\pi^+\pi^-\mathrm{MM}, \quad (5a)$$

$$\Lambda\pi^+\pi^+\pi^-\pi^-\pi^0, \quad (5b)$$

$$(\Lambda^0, \Sigma^0)\mathrm{MM}. \quad (6)$$

The number of events in each channel is displayed in Table I, but it should be emphasized that different protions of the film were analyzed for each particular channel and therefore only fully corrected numbers may be meaningfully compared.

The complete unselected $K\bar{K}$ mass spectrum[4] from Reactions (1) and (2) is shown in Fig. 1(a). The φ and f^* signals are manifestly clear, the former occurring with essentially no background, and the latter with $\lesssim 30\%$ background. Fitting a Breit-Wigner shape in the region of the f^* peak gives a mass value of $M = 1513 \pm 7$ MeV and a width $\Gamma = 87 \pm 15$ MeV. In subsequent analysis we optimize the f^*-to-background ratio [where f^* region is defined by $1460 \leq M(f^*$ decay products$) \leq 1580$ MeV], by making use of a peripheral selection criterion: $-1.0 \leq \cos\theta_\Lambda \leq -0.6$, where θ_Λ is the center-of-mass production angle of the Λ.

Various individual contributions to the $K\bar{K}$ peak of Fig. 1(a), i.e., those due to K^+K^-, all $K^0\bar{K}^0$, and the $K_1^0K_1^0$ modes, all satisfying the peripheral criterion, are shown, respectively, in Figs. 1(b), 1(c), and 1(d). From the latter two we may ascertain the well-known $K_1^0K_1^0$ vs $K_1^0K_2^0$ decay-rate correlation which determines the charge conjugation number C. This correlation, parametrized in terms of the ratio[5] R, gives $R = 0.46 \pm 0.2$. This value is to be compared with the theoretical expectation of $R = -1$ for $C = -1$ or $R = +\frac{1}{5}$ for $C = +1$, and thus establishes $C = +1$ by about seven standard deviations. Also, the data of Figs. 1(a) and 1(c) permit us to re-examine previous evidence concerning the isospin I of the f^*. This evidence, involving the relative rates[6] of $\Sigma^0 f^{*0}$ vs $\Sigma^\pm f^{*\mp}$, is found to remain consistent with $I = 0$. Finally, the fully corrected ratio $K^+K^-/K^0\bar{K}^0$, inferred from Figs. 1(b) and 1(c), is consistent with unity, as expected. Thus, we consider the K^+K^- and $K^0\bar{K}^0$ contributions as a unit in order to obtain the total $K\bar{K}$ branching fraction, as indicated in Table I.

We now consider other possible decay modes, beginning with $f^* \to \pi + \pi$. The relevant final

Table I. Branching ratios for various decay modes of the $f^*(1500)$ meson.

Final state	Total No. events	Fully corrected No. events (with visible Λ) in f^* region	Decay mode	Branching ratios Without K^*K signal	With K^*K signal
$(\Lambda,\Sigma)K\bar{K}$	502	200 ± 32	$K\bar{K}$	0.80 ± 0.13	0.72 ± 0.12
$(\Lambda,\Sigma)\pi^+\pi^-$	1150	<36	$\pi\pi$	<0.14	<0.13
$(\Lambda,\Sigma)KK\pi$	333	<28 or 28 ± 21	K^*K	<0.11	0.10 ± 0.10
$(\Lambda,\Sigma)\pi^+\pi^-$MM + $(\Lambda,\Sigma)\pi^+\pi^-\pi^+\pi^-\pi^0$	1200	50 ± 25	$\eta^0\pi\pi$	0.20 ± 1.10	0.18 ± 0.10
(Λ,Σ)MM	900	15 ± 50	$(\eta^0\eta^0)$ [a]	<0.4	<0.36

[a]Ref. 11.

states, $(\Lambda^0,\Sigma^0)\pi^+\pi^-$, contain significant amounts of hyperon resonances (Y^*). However, subtraction of the Y^*'s turns out to have no appreciable effect on the observed $\pi\pi$ mass distribution. The $M(\pi\pi)$ spectrum satisfying the peripheral criterion mentioned above is shown in Fig. 2(a). This spectrum can be roughly interpreted as the incoherent superposition of contributions from ρ, f^0, and phase-space background. There is no excess of events in the f^*-mass region. A two-standard-deviation upper limit is given in Table I.

Reactions (4) provide the data relevant to the search for a K^*K decay mode. The $M(K^*K)$ spectrum, shown in Fig. 2(b), is peaked at low masses. This is inconsistent with the behavior expected from phase space, represented by the curve of Fig. 2(b). However, experience with such potentially complicated four-body final states indicates that this is not unusual.[7] Such low K^*K mass peaking may be associated either with kinematic effects of the "Deck type"[8] or the existence of appropriate resonances,[9] or both. Thus there is no clear-cut evidence for a K^*K decay mode at present. However, because this result depends upon one's interpretation of the background, we present two versions of branching-ratio estimates, one assuming a small (~8-event) signal and one assuming no signal, quoted as an upper limit. See Table I.

Next we consider a possible $\eta^0\pi\pi$ decay mode of the f^*, which would appear (primarily) in

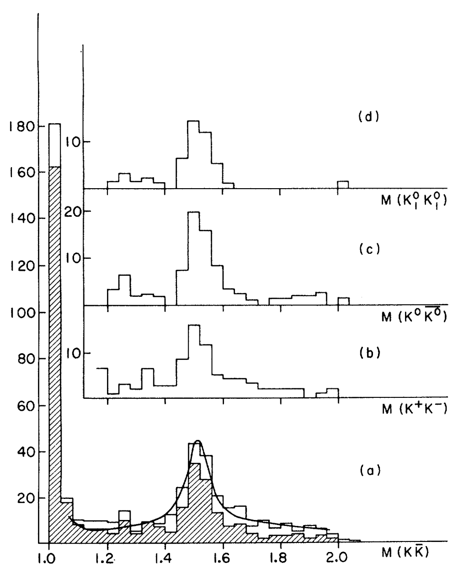

FIG. 1. (a) $K\bar{K}$ mass spectrum from Reactions (1) and (2). The shaded region corresponds to $\cos\theta_\Lambda < -0.6$ (see text). (b), (c) Peripheral mass spectra from Reactions (2) and (1). (d) Peripheral $K_1^0K_1^0$ spectrum from Reaction (1).

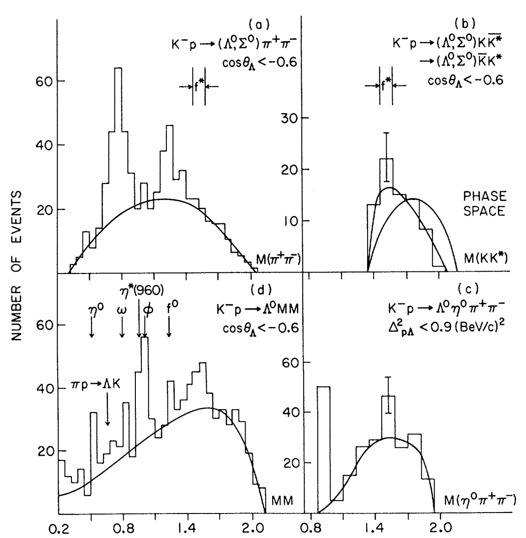

FIG. 2. Mass spectra used in search for various f^* decay modes.

Reactions (5a) and (5b). For (5a), we select events in which MM lies in the η^0 (520- to 580-MeV) interval and for which there is a (subsequent) kinematic fit to the $\eta^0\pi^+\pi^-$ hypothesis, while for (5b), we select all events with at least one $\pi^+\pi^-\pi^0$ permutation in the η^0 interval. These criteria, when coupled with a momentum-transfer selection $[\Delta_{p\Lambda}^2 < 0.9\ (\mathrm{BeV})^2]$, yield the mass spectrum for all products recoiling against the Λ^0 shown in Fig. 2(c). (In this particular case the Δ^2 selection is preferable to the standard peripheral θ cut since it yields a better signal-to-noise ratio.) In addition to the large η^* peak, one sees a two-standard-deviation $\eta^0\pi\pi$ signal at the f^* mass. The corresponding branching fraction is given in Table I.

The search for possible neutral decay modes of the f^*, such as $\eta^0\eta^0$, is carried out by examining the peripheral neutral MM spectrum from Reaction (6), as shown in Fig. 2(d). Known resonances appear quite distinctly at the lower mass values, and provide the opportunity of ascertaining the background level at the positions[10] corresponding to the η^0, ω^0, η^*, and φ mesons. For higher mass values the background level is more severe. However, after extrapolating a smooth background curve from lower to higher mass values, and normalizing to the f^0 signal, one observes a clear f^* signal of 31 ± 8 events taking into account the resolution in the channel. Since one expects a signal of 28 ± 6 events in this plot due to (i) uncharged K_1K_1 decays, (ii) K_2K_2 decays, and (iii) ($\eta^0\to$ neutrals) $\pi^0\pi^0$, there is no significant indication of any additional neutral component. Consequently, in Table I, we quote only an appropriate two-standard-deviation upper limit.[11] In the following Letter,[12] we shall interpret this as an upper limit for $\eta^0\eta^0$ decay, since this is the most likely candidate for an additional neutral mode.

We turn now to the question of the spin and parity of the f^*. The existence of an $\eta^0\pi\pi$ or K^*K decay mode would rigorously rule out $J^P = 0^+$. Since such modes are observed only at the two-standard-deviation level or below, more significant information on J^P is obtained from $K\bar{K}$ decay angular distributions. The distribution[13] $f(\theta)$, where θ is the angle between the incoming K^- and one outgoing kaon in the f^* rest frame, is shown in Fig. 3(a) for all f^* events in which both K_1's are observed. The anisotropy is evident. Since [as one can clearly see from Fig. 1(d)] there is essentially zero background in this sample, the very small χ^2 probability for isotropy ($\lesssim 0.1\,\%$) provides strong evidence against $J^P = 0^+$. In contrast, the fits[14] for 2^+ and 4^+ are both perfectly consistent with the data.

Further information may be obtained from the entire (peripheral) $K\bar{K}$ sample of Fig. 1(a). Here there are many more events in the f^* peak, but the background contribution is not ignorable. Thus, in this case, it is profitable to examine the structure of $f(\theta,\varphi)$ as a function of $K\bar{K}$ effective mass.

The $M(K\bar{K})$ dependence of the moments of the distribution a_l^m, defined by

$$f(\theta,\varphi)=\sum_{l=0}^{2J}(\tfrac{1}{2})a_l^m[Y_l^m(\theta,\varphi)+Y_l^{-m}(\theta,\varphi)],$$

are displayed in Fig. 3(b). One sees no significant variation in any moment at mass values outside the φ and f^* region. In the φ region a_0^0 and a_2^2 are large, as one would expect, because a_0^0 is simply proportional to the number of $K\bar{K}$ events, and because the production of

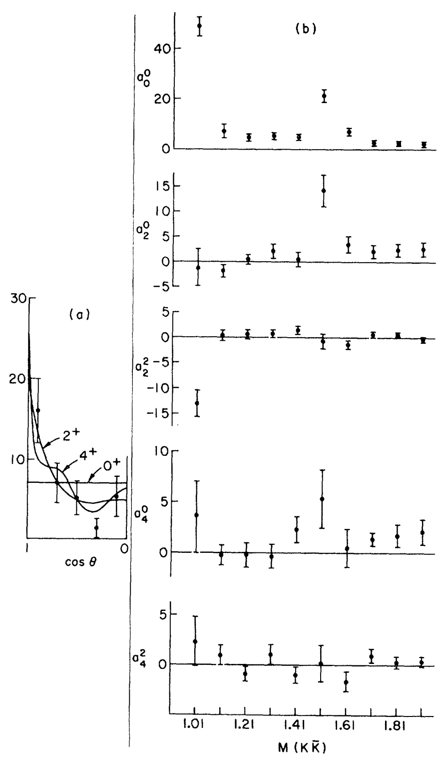

FIG. 3. (a) Polar angle distribution of decay kaon from $f^*\to K_1^0+K_1^0$ in f^* rest frame. (b) Moment (a_l^m) distribution of $K\bar{K}$ events plotted against $K\bar{K}$ effective mass (see text).

a spin-1 resonance (partially) via K^* exchange requires a significant $\cos 2\varphi$ component.[15] In the f^* region both a_2^0 and a_4^0 appear to be large. Since a large a_4^0 must arise from a $J \geq 2$ resonance, it is only the relatively weak statistical significance of the a_4^0 signal which prohibits a firm rejection of the spin-zero hypothesis. The significance of the a_2^0 peaking is beyond question, and also suggests a $J \geq 2$ resonance, but it is not a unique indication. The simplest alternative possibility is the existence of an s-wave resonance interfering coherently with a d-wave background. Such a possibility must be considered extremely remote on two accounts. Firstly, as we noted above, the a_4^0 distribution shows no sign of a d-wave background. Secondly, the K_1K_1 mass distribution of Fig. 1(d), where even-l-wave background intensity components must appear, gives no indication of any d-wave background.

Taking all the above evidence into account we conclude that the f^* has $J \geq 2$. The sample size is insufficient to warrant study of higher l-wave moments which could in principle distinguish among high spin values.

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[1]V. Barnes et al., Phys. Rev. Letters 15, 322 (1965).

[2]The final states considered in Reaction (4) are (a) $\Lambda^0K^0K^-\pi^+$, (b) $\Lambda^0\bar{K}^0K^+\pi^-$, and (c) $\Lambda^0K^0\bar{K}^0\pi^0$, where in the first two reactions both neutral particles are required to decay via their visible modes and in (c) all three neutrals are required to decay via their charged modes.

[3]The symbol MM denotes missing mass due to one or more missing particles.

[4]All Reaction (1)-type events containing two V^0's were kinematically tested for the π-induced reactions $\pi^-p \rightarrow K_1K_1n$ and $\pi^-p \rightarrow \Lambda^0K^0$. Such events were removed when the χ^2 probability was higher for the pion than the corresponding kaon interpretation. The number of events removed is consistent with expectations based on the known π flux and partial cross sections.

[5]$R = (N_2-N_1)/(N_2+N_1)$ where N_2 is the number of events with two visible K_1 decays and N_1 is the number of events with one visible K_1 decay.

[6]The Σ^0f^{*0} rate is roughly determined to be $\sim\frac{1}{3}$ of the Λ^0f^{*0} rate on the basis of the unfitted hyperon mass distribution from events in which both K's are observed in channels (1) and (2). There is no indication of charged f^* production.

[7]R. T. Deck, Phys. Rev. Letters 13, 169 (1964); U. Maor and T. A. O'Halloran, Jr., Phys. Letters 15, 281 (1965); M. Goldberg et al., Phys. Rev. Letters 18, 680 (1967).

[8]In this instance the lower vertex of the π-exchange diagram involves $\pi p \rightarrow \Lambda^0K^0$ associated production rather than elastic scattering. However, the former is known to produce forward K^0's, which would lead to a low mass K^*K enhancement.

[9]For instance, the E meson with mass $M(K\pi\pi) = 1420$ MeV.

[10]The charged modes of these resonances have been studied in other channels. The normalization at the (unresolved) η^* and φ mass region indicates a neutral surplus here. This will be discussed in a future publication.

[11]This upper limit corresponds to two times the error in the (fully corrected) difference signal of $\{(31-28) \pm 10\}\times 5$ events. The large size of this upper limit is due to the large Clebsch-Gordan, visibility, and data-fraction correction factors of ~ 5.

[12]D. Bassano et al., following Letter [Phys. Rev. Letters 19, 968 (1967)].

[13]$f(\theta)$ must be folded about $\theta = 90°$ due to the indistinguishability of the K^0 and $\bar{K}^0$.

[14]The azimuthal single (φ) distribution has also been studied and found to yield no useful information, such as that which would suggest a particular exchange mechanism. The 2^+ and 4^+ fits are made assuming no restrictions on the density matrix elements.

[15]See, for example, J. D. Jackson, Rev. Mod. Phys. 37, 484 (1965).