f^* PRODUCTION IN K^-p INTERACTIONS AT 5.5 GeV/c †

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The f^* meson was observed, with a partial cross section of 14 ± 4 μb, in the reaction $K^- + p \rightarrow \Lambda + f^*$, at 5.5 GeV/$c$. Its mass was measured as 1515 ± 7 MeV, with a width of 35 ± 25 MeV, considerably narrower than previously measured. The decay into $K\bar{K}$ was the dominant mode, with no significant evidence for decay into $\pi\pi\eta$, $\pi\pi$, $K^*\bar{K}$, or $\bar{K}^*K$. The production and decay angular distributions are presented and analyzed in terms of the spin-density matrix formalism.

We report on a study of the f^* meson produced in the reaction $K^- + p \rightarrow \Lambda + f^*$ at an incident K^- momentum of 5.5 GeV/c. The final states investigated here are given in Table I along with the number of fits in each channel. These results are based on the analysis of ~400 000 pictures taken in the 30-in. hydrogen bubble chamber at the Argonne zero-gradient synchrotron, exposed to the high-purity separated beam.[1] The statistical level of the exposure corresponds to ~7 events/μb.

We shall at first confine our attention to the $\Lambda K\bar{K}$ final state which accounts for essentially all of the observed f^* events in our sample and for which the resolution of ambiguities is a relatively straightforward matter. Within the $\Lambda K\bar{K}$ final state we distinguish between the two possibilities ΛK^+K^- and $\Lambda K^0\bar{K}^0$. In our sample the former are four-constraint fits belonging to the two-prong + V topology, while the latter are usually one-constraint fits (0-prong + $2V$). Detailed investigations indicate that the small backgrounds in these final states do not affect our conclusions.[2,3]

The $K\bar{K}$ invariant-mass distribution given in Fig. 1(a) shows that the dominant features of the $\Lambda K\bar{K}$ final state are strong φ production and a mass peak corresponding to the less well-established f^* meson.[4,5] The ΛK^+K^- events are distinguished from the $\Lambda K^0\bar{K}^0$ events by cross hatching. Using both types of events and fitting a curve consisting of two Breit-Wigner functions plus phase space, one obtains for the mass and width of the f^* the values

$$M(f^*) = 1515 \pm 7 \text{ MeV},$$

$$\Gamma(f^*) = 35 \pm 25 \text{ MeV},$$

where the quoted width has been corrected for our experimental mass resolution.[6]

Our measured width is considerably sharper than the value of 85 MeV reported by Barnes et al.[4] and is in good agreement with the predictions of SU(3) and quark models.[7,8]

After correcting for such effects as undetected neutrals, differences in fiducial volume, etc., the branching ratio for f^* decay into $K^0\bar{K}^0$ relative to K^+K^- is measured to be 1.0 ± 0.3, in good agreement with the expected value of 1.

In our sample there are relatively few events in the $\Lambda K^0\bar{K}^0$ final state for which both neutral K mesons were observed to decay into $\pi^+\pi^-$, thereby enabling one to classify them as $K_1^0K_1^0$ events. Of the 23 $K_1^0K_1^0$ events, one is to be found in the φ peak, while five events are in the region of the f^* peak. This is consistent with the observation of Barnes et al.,[4] based on considerably better statistics in this particular channel, that the f^* has $C = +1$ and can decay into $K_1^0K_1^0$ in contrast to the φ which has $C = -1$ and cannot decay into $K_1^0K_1^0$ but rather into $K_1^0K_2^0$.

Table I. Final states investigated.

Final state	No. of fits
ΛK^+K^-	172
$\Lambda K^0\bar{K}^0$	74
$\Lambda\pi^+\pi^-$	564
$\Lambda\pi^+\pi^-(\eta)$	2031
$\Lambda K^0\bar{K}^0(\pi^0)$	12
$\Lambda K^+\pi^-\bar{K}^0$	29 [a]
$\Lambda K^-\pi^+K^0$	32 [a]

[a]Two-prong + $2V$ events only.

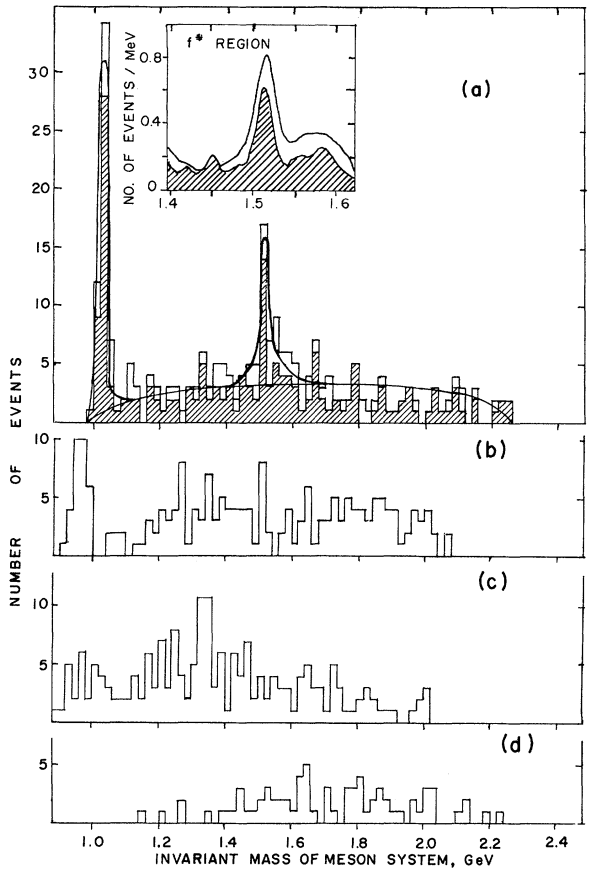

FIG. 1. (a) The invariant-mass distribution for a total of 246 events fitting the hypothesis $K^- + p \to \Lambda + K + \bar{K}$. The ΛK^+K^- events are differentiated from the $\Lambda K^0\bar{K}^0$ events by cross hatching. The curve consists of two Breit-Wigner functions plus phase space, fitted to the entire sample of both types of events. The insert shows a more detailed mass ideogram in the region of the f^*. (b) Missing-mass (MM) distribution in the reaction $K^- + p \to \Lambda + MM$ for those events that fit the hypothesis $K^- + p \to \Lambda + \pi^+ + \pi^- + \eta$. Only those events with $\Delta^2(MM) \leq 0.7$ $(\mathrm{GeV}/c)^2$, and having a mass for the missing η within ±50 MeV of the known η mass, have been plotted. (c) Invariant-mass distribution of the $\pi^+\pi^-$ system for events fitting the hypothesis $K^- + p \to \Lambda + \pi^+ + \pi^-$ and having $\Delta^2(\pi^+\pi^-) \leq 0.7$ $(\mathrm{GeV}/c)^2$. (d) Invariant-mass distribution of the $K\bar{K}\pi$ system for events fitting $\Lambda K^0 K^0(\pi^0)$ or $\Lambda K^+\pi^- K^0$ or $\Lambda K^-\pi^+ K^0$, for which at least two neutral decays were detected.

Figure 2(a) shows a Chew-Low plot for the $\Lambda K\bar{K}$ final state. For the f^*, most of the events appear in a single cluster corresponding to forward peripheral production as expected from single-meson-exchange processes; there is no evidence for a significant backward peak such as might arise from baryon exchange. A similar momentum-transfer distribution is obtained for the φ meson,[9] as may also be

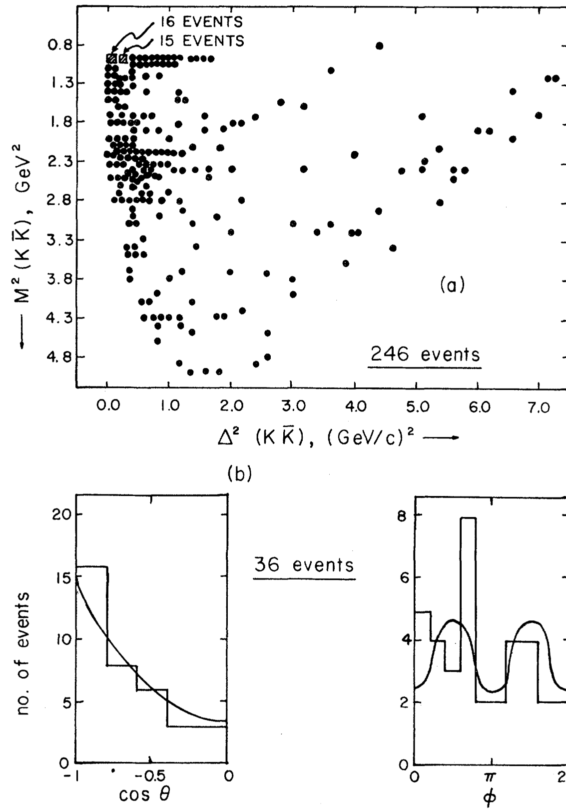

FIG. 2. (a) Production distribution of the $K\bar{K}$ system in the reaction $K^- + p \to \Lambda + K + \bar{K}$, showing $\Delta^2(K\bar{K})$, the square of the four-momentum transfer to the $K\bar{K}$ system versus $M^2(K\bar{K})$, the square of the mass of that system. (b) Decay distribution for $f^* \to K + \bar{K}$, following its production via $K^- + p \to \Lambda + f^*$. The angles θ and φ are the polar and azimuthal angles of the momentum defined by the decay products $K\bar{K}$, with respect to the incident K^- direction, as measured in the f^* rest frame. The distribution in θ has been folded about $\theta = 0$. The solid curves are the best fit to 2^+. Events were selected to have $1.445 \leq M(K\bar{K}) \leq 1.585$ GeV, and $\Delta^2(K\bar{K}) \leq 0.7$ $(\mathrm{GeV}/c)^2$.

seen in Fig. 2(a).

The f^* production and subsequent decay into $K\bar{K}$ has been investigated in terms of the usual spin-density-matrix formalism.[10] The observation of the mode $K\bar{K}$ in a strong decay restricts the spin parity of the f^* to be 0^+, 1^-, 2^+, 3^-, etc. The possibilities 1^-, 3^-, $\cdots$ have already been ruled out by Barnes et al.[4] on the basis of their unequivocal observation of a $K_1{}^0K_1{}^0$ decay mode.

For a 2^+ resonance produced by pseudoscalar or vector-meson exchange, the expected decay angular distribution is given by[11]

$$W(\theta, \varphi) = C\{3\rho_{00}(\cos^2\theta - \tfrac{1}{3})^2 + 4\sin^2\theta\cos^2\theta[\tfrac{1}{2}(1-\rho_{00}) - \rho_{1,-1}\cos 2\varphi]\},$$

where the angles θ and φ are the usual polar and azimuthal angles of the momentum defined by the decay products $K\bar{K}$, with respect to the incident K^- direction, as measured in the rest frame of the f^*. Events were selected to have a square of the four-momentum transfer $\Delta^2 \leq 0.7$ $(\mathrm{GeV}/c)^2$. The fit to this distribution[12] gives for the density matrix elements the values $\rho_{00} = 0.4 \pm 0.2$ and $\rho_{1,-1} = 0.15 \pm 0.15$. The observed angular distributions in θ and φ together with the best fit curves are shown in Fig. 2(b), from which it is apparent that the fit is quite satisfactory. Effects of absorption have been neglected; so the values of the density matrix elements do not directly yield the fraction of pseudoscalar and vector exchange.

In contrast to the satisfactory fit which can be obtained to the hypothesis that the f^* has spin-parity of 2^+, the fit to 0^+ is very poor, yielding a χ^2 probability of less than 5% for the assumption of isotropy for the $\cos\theta$ distribution shown in Fig. 2(b). We therefore conclude, with Barnes et al.,[4] that 0^+ may be ruled out and that the only possible spin-parity assignments for the f^* are 2^+, 4^+, etc.

We turn next to a discussion of final states other than $\Lambda K\bar{K}$, in order to investigate other decay modes of the f^*. We confine our attention to the final states given in Table I, and in so doing exclude from the scope of the present investigation other possible decay modes of the f^*.

There are approximately 2000 fits to the hypothesis $\Lambda\pi^+\pi^-\eta$. The ambiguities were primarily with the hypothesis $\Lambda\pi^+\pi^-\pi^0$, and in addition, the possibility of multiple neutrals is also present. Possible f^* production in this channel was investigated by means of the missing-mass (MM) distribution obtained by treating the $\Lambda\pi^+\pi^-\eta$ fits as the reaction $K^- + p \rightarrow \Lambda + MM$. Cuts were made to enrich and purify the sample. In particular since f^* production is very peripheral, we imposed the restriction $\Delta^2(MM) \leq 0.7$ $(\mathrm{GeV}/c)^2$ and also insisted that the calculated value for the mass of the missing η lie within ±50 MeV of the known η mass. There was no significant evidence for the f^* in this final state, as is seen in Fig. 1(b).

There were approximately 560 fits to the hypothesis $\Lambda\pi^+\pi^-$. The ambiguities were primarily with the hypothesis $\Sigma^0\pi^+\pi^-$, but a previous study[3] of this final state has shown that the events as a whole represent $\Lambda\pi^+\pi^-$ events with relatively little contamination from $\Sigma^0\pi^+\pi^-$. The $\pi^+\pi^-$ invariant-mass distribution for these events did not reveal any appreciable f^* signal, as is apparent from Fig. 1(c).

The last final state looked at was the $\Lambda K\bar{K}\pi$. This state is best studied in those topologies for which more than one V was detected. This sample of events is relatively free of serious ambiguities, because of the editing of individual events at the scanning table. This editing was performed by physicists, employing such additional data as ionization as well as other information which could be readily extracted by direct viewing of the event. No appreciable signal was observed for the f^* decaying into $K^*(890)\bar{K}$, or $\bar{K}^*(890)K$, or into the three-body mode $K\bar{K}\pi$, as is evident from Fig. 1(d).

From the preceding analysis we conclude that, of those investigated, $K\bar{K}$ is the dominant decay mode of the f^* and that the frequency of decay into $\pi\pi\eta$, $\pi\pi$, and $(K^*\bar{K} + \bar{K}^*K + K\bar{K}\pi)$ are ≤ 0.3, ≤ 0.2, and ≤ 0.4 of the $K\bar{K}$ mode, respectively, all at the 60% confidence level.

Finally, we find the partial cross section for the reaction

$$K^- + p \rightarrow \Lambda + f^*,$$

with subsequent decay of the f^* into the $K\bar{K}$ final state only, to be 14 ± 4 μb.

This experiment would not have been possible without the help of the crews of the zero-gradient synchrotron and bubble chamber, as well as the careful work of our scanners and measurers. To all of them we extend our thanks.

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[1]R. Ammar, T. H. Fields, M. Derrick, E. L. Goldwasser, M. L. Good, U. E. Kruse, D. Reeder, F. Schweingruber, and J. D. Simpson, in Proceedings of the International Conference on Instrumentation for High Energy Physics, Stanford, 1966 (International Union of Pure and Applied Physics and U. S. Atomic Energy Commission, Washington, D. C., 1966), p. 620.

[2]For the ΛK^+K^- fits the ambiguities are primarily with the $\Sigma^0K^+K^-$ hypothesis (two-constraint fit) and the $\Lambda\pi^+\pi^-\pi^0$ hypothesis (one-constraint fit). By use of the program FAKE [G. R. Lynch, University of California Radiation Laboratory Report No. UCRL-10335, 1966 (unpublished)], it could be shown that ΛK^+K^- events usually fit the $\Lambda\pi^+\pi^-\pi^0$ hypothesis, while the converse was rarely true, so that the four-constraint ΛK^+K^- fits were generally more believable than the one-constraint $\Lambda\pi^+\pi^-\pi^0$ fits. The handling of the Λ/Σ^0 ambiguities is discussed in Ref. 3. In this manner it was con-

cluded that the group as a whole represented ΛK^+K^- events, with negligible contamination from the other two final states, and the events were so assigned. The sample of $\Lambda K^0\bar{K}^0$ fits presented here represents ~30% of the $\Lambda K\bar{K}$ final state. The group as a whole is consistent with being all $\Lambda K^0\bar{K}^0$ events, exhibiting properties similar to the sample of ΛK^+K^- events, and they were therefore assigned as such.

[3]J. Mott, R. Ammar, R. E. P. Davis, W. Kropac, F. Schweingruber, M. Derrick, T. Fields, L. Hyman, J. Loken, and J. Simpson, Phys. Rev. Letters 18, 355 (1967); J. Mott, Ph.D. thesis, Northwestern University, 1967 (unpublished).

[4]V. E. Barnes, B. B. Culwick, P. Guidoni, G. R. Kalbfleisch, G. W. London, R. B. Palmer, D. Radojicic, D. C. Rahm, R. R. Rau, C. R. Richardson, N. P. Samios, J. R. Smith, B. Goz, N. Horwitz, T. Kikuchi, J. Leitner, and R. Wolfe, Phys. Rev. Letters 15, 322 (1965).

[5]G. S. Abrams, B. Kehoe, R. G. Glasser, B. Sechi-Zorn, and G. Wolsky, Phys. Rev. Letters 18, 620 (1967).

[6]Our experimental mass resolution function has a width of ~18 MeV for the four-constraint ΛK^+K^- fits and ~24 MeV for the one-constraint $\Lambda K^0\bar{K}^0$ fits. The over-all resolution function for the particular admixture of all kinds of fits present in our sample has a width of ~20 MeV.

[7]Sheldon L. Glashow and Robert Socolow, Phys. Rev. Letters 15, 329 (1965). The partial width predicted for the $K\bar{K}$ decay mode is 31 MeV, but there is also an appreciable contribution (17-MeV partial width) predicted for the $K^*\bar{K}+\bar{K}^*K$ mode. A more recent estimate by M. Goldberg et al., Nuovo Cimento 45A, 169 (1966), puts this latter partial width at 7 ± 4 MeV. The results are also sensitive to the input value for the width of the A_2 which recently appears to show a complex structure [G. Chikovani et al., Phys. Letters 25B, 44 (1967)].

[8]Jack L. Uretsky, "On the Bosons of Zero Baryon Number as Bound States of Quark-Antiquark Pairs," in High Energy Theoretical Physics, edited by Hadi Aly (to be published). The total width obtained in this calculation is ~35 MeV.

[9]The absence of baryon exchange, pointing to a weak $N\bar{N}\varphi$ coupling, as predicted by quark and ω-φ mixing models, has already been discussed in Ref. 3.

[10]K. Gottfried and J. D. Jackson, Nuovo Cimento 33, 309 (1964).

[11]R. H. Dalitz, in Proceedings of the International School of Physics Enrico Fermi, Course XXXIII (Academic Press, Inc., New York, 1966), p. 141.

[12]A satisfactory fit for the spin density matrix elements could also be obtained assuming a spin parity of 1^- for the f^*, but it was discarded on the basis of the $K_1{}^0K_1{}^0$ decay mode observed by Barnes et al., Ref. 4.

MULTICHANNEL PHASE-SHIFT ANALYSIS OF $\bar{K}N$ INTERACTION IN THE REGION 0 TO 550 MeV/c*

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Multichannel phase-shift analysis has been performed on available experimental data for all channels of K^-p and $K_2{}^0p$ interactions in the momentum region 0 to 550 MeV/c.[1] In this analysis, the multichannel effective-range parametrization of Ross and Shaw[2] has been applied. The results on the S_{01} phase shift give the mass and width of the $\bar{K}N$ bound state which are, respectively, lower and larger than the values obtained from the previous constant-scattering-length analysis. The P_{13} phase shift shows that $Y_1{}^*(1385)$ is due mainly to strong $\Lambda\pi$ interaction and that its coupling to $\bar{K}N$ is very weak. Also in this analysis, the Fermi-Yang ambiguity in $I=0$ K^+n phase shift of Stenger et al.[3] can be resolved and the Yang set is definitely favored.

Available experimental cross sections and angular distributions from approximately 22 000 events of the following ten reactions below 550 MeV/c have been analyzed:

$$K^-+p\to K^-+p,$$
$$K^-+p\to\bar{K}^0+n,$$
$$K^-+p\to\Sigma^++\pi^-,$$
$$K^-+p\to\Sigma^-+\pi^+,$$
$$K^-+p\to\Sigma^0+\pi^0,$$
$$K^-+p\to\Lambda+\pi^0,$$
$$K^-+p\to\Lambda+\pi^++\pi^-,$$
$$K_2{}^0+p\to K_1{}^0+p,$$
$$K_2{}^0+p\to\Sigma^0+\pi^+,$$
$$K_2{}^0+p\to\Lambda+\pi^+.$$

The experimental results come mainly from the following three experiments. The cross sections and angular distributions from 0 to