EXISTENCE AND PROPERTIES OF A NONSTRANGE MESON OF MASS 1500 MeV/c^2*

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In this note, we present evidence for the existence[1] and properties of a nonstrange meson which we call the f^*. An enhancement is observed in the K_1K_1 system with mass $M \approx 1500$ MeV/c^2 and width $\Gamma \approx 85$ MeV/c^2. The existence of this decay mode requires that the f^* be even under charge conjugation, C, or equivalently, that it have even spin and parity. We also observe the decay of the f^* into KK^*, which excludes a 0^+ spin-parity assignment.

We have studied K^-p interactions at 4.6- and 5.0-BeV/c incident K^- momentum[2] using the Brookhaven National Laboratory 80-in. hydrogen bubble chamber. The K path length is equivalent to about nine events per microbarn of cross section. Data were analyzed using the TRED-KICK system.[3] The evidence for the existence of the f^* meson comes from a study of the final states summarized in Table I.

We first discuss the $(\Lambda^0, \Sigma^0)K^0\bar{K}^0$ channel.[4] The Dalitz plot for this channel[5] is shown in Fig. 1, together with the projections on both axes. The phase-space curves drawn on the projections give a rough estimate of the background. The very striking peak in the region 1.00 to 1.05 (BeV/c^2)^2 is due to the φ meson. In addition, a marked enhancement is observed at about 2.25 (BeV/c^2)^2. In the interval between 2.125 and 2.375 (BeV/c^2)^2, there are 29 events where about 10 are expected.[6] The $M^2(Y^0K^0)$ projection of the Dalitz plot (with the φ region excluded) shows no significant departure from phase space, although one might expect Ξ^* and N^* resonances[7] to be produced. Thus the $K\bar{K}$ enhancement at 2.25 (BeV/c^2)^2 is not due to a "reflection."

Table I. Number of events per final states.

Final state	Number of events
$(\Lambda^0, \Sigma^0)K^0\bar{K}^0$	162
$\Sigma^\pm K^\mp K^0$	23
$\Lambda^0K^0\bar{K}^0\pi^0$	13
$\Lambda^0\bar{K}^0K^+\pi^-$	24
$\Lambda^0\bar{K}^0K^-\pi^+$	36
$\Sigma^\pm K^0\bar{K}^0\pi^\mp$	92

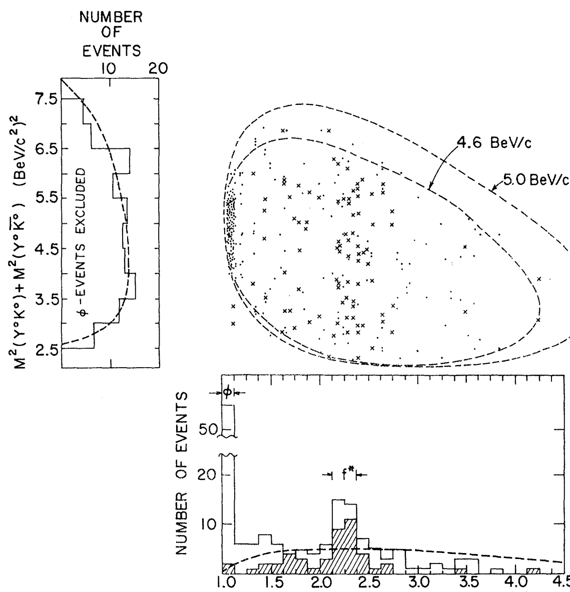

FIG. 1. $Y^0K^0\bar{K}^0$ Dalitz plot for 162 events plotted twice. The dots are for events with only one K decay visible, i.e., $K_1 \to \pi^+ + \pi^-$. The crosses are for events with two visible K_1 decays. In the $M^2(K\bar{K})$ projection, each event is plotted once. The shaded area is for those events with two visible K_1 decays. In the $M^2(Y^0K^0)$ projection, outside the φ region, each combination is plotted as $\frac{1}{2}$ an event.

We emphasize that the f^* enhancement is due primarily to the shaded events, those with two visible (i.e., $K_1 \to \pi^+ + \pi^-$) K_1 decays. It is obvious that we are dealing with the strong decay of a neutral particle in which C is conserved. If the f^* is even (odd) under C, the observed enhancement can only be due to its K_1K_1 (K_1K_2) decay mode.[8] We define the ratio, R, as $(N_2-N_1)/(N_2+N_1)$, where N_1 is the num-

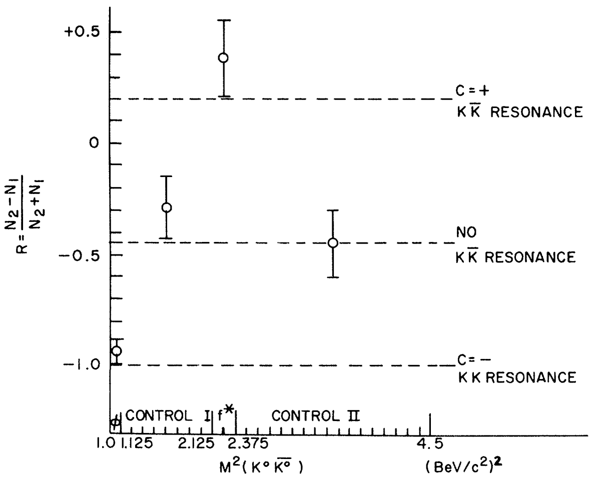

FIG. 2. Ratio, $(N_2-N_1)/(N_2+N_1)$, in different mass regions. N_1 is the number of events with one visible K_1 decay; N_2 is the number of events with two visible K_1 decays.

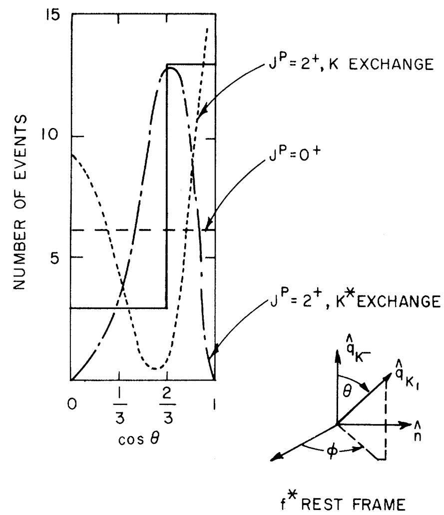

FIG. 3. The distribution of the angle between the incident K^- and one of the decay particles in the resonance rest frame. The coordinate system is shown in the inset.

ber of events with one visible K_1 decay and N_2 is the number of events with two visible K_1 decays Then[9] (a) $R=-\frac{5}{11}$ if there is no $K\bar{K}$ resonant state; (b) $R=+\frac{1}{5}$ if there is a $C=+K\bar{K}$ resonant state; (c) $R=-1$ if there is a $C=-K\bar{K}$ resonant state. We have determined[10] R in the φ region, the f^* region, and two control regions. This is shown in Fig. 2. It is clear that the φ events satisfy the $C=-K\bar{K}$ decay correlation, as expected, while the f^* events behave as the decay of a $C=+K\bar{K}$ resonant state. The value of R in each control region is consistent with the hypothesis of an uncorrelated background of $K\bar{K}$ events. Since $C=P$ (parity) for the f^*, we conclude that its spin and parity must be even: $J^P=0^+, 2^+$, etc.

To distinguish among the different possible spin-parity assignments for this decay mode, we now consider the f^*-decay angular distributions. In order to minimize background, we use only the 19 f^* events in the K_1K_1 subsample where both K_1 decays are visible. Since the f^* is produced peripherally (i.e., about 90% of the events have $\cos\theta_\Lambda^{\text{prod}} \leq -0.4$), we assume the one-particle-exchange model. In this analysis the distributions are folded to take into account the indistinguishability of the decay particles. The experimental azimuthal (Treiman-Yang) angular distribution is isotropic; thus K and/or K^* exchange is possible. The distribution of the angle between the incident K^- and one of the decay particles in the resonance rest frame is shown in Fig. 3. Neglecting background interference,[11] a spin-0 f^* would decay insotropically. The experimental distribution has a 0.5% probability of being isotropic. On the other hand, it is consistent with a 2^+ assignment with a mixture of both K and K^* exchange.[12]

Further evidence for the existence of the f^* comes from a study of the $\Lambda K\bar{K}\pi$ final states.[13] An investigation of the $K\bar{K}\pi$ mass spectrum reveals an f^* enhancement only when a $K\pi$ combination is consistent with a K^*.[14] The KK^* mass-squared histogram is shown in Fig. 4.

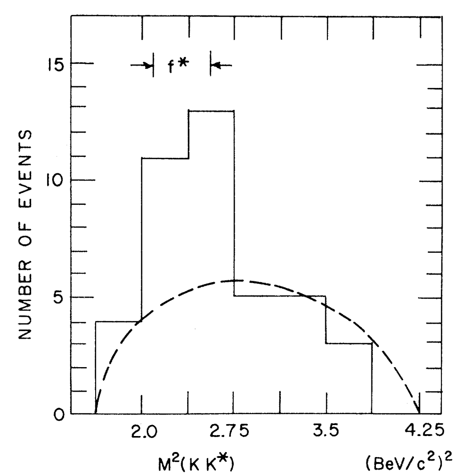

FIG. 4. The $M^2(KK^*)$ histogram for the 41 events in the $\Lambda KK\pi$ final state. The K^* is defined to be between 840 and 940 MeV/c^2.

The smooth curve is the phase space for ΛKK^*, normalized to the events in the high effective-mass region. The observed peak[15] is centered at about the same mass[16] and has about the same width as the K_1K_1 enhancement. The statistical significance of this peak is comparable to that found in the K_1K_1 mode. There is little or no evidence for "reflections" of $\Lambda\pi$ final-state interactions appearing in the KK^* histogram. We also note, as in the K_1K_1 final state, that the production angular distribution of the events in the KK^* peak is peripheral. The existence of the KK^* decay mode automatically excludes a 0^+ spin-parity assignment. The cross section for f^* production and decay through these two modes is roughly 45 μb with a relative rate of K_1K_1 to KK^* of about 1.

We have looked for other possible decay modes of the f^* in multipion final states. On the basis of an analysis of about 2% of our "one-V^0+two-prong" events, we find no evidence for 2π or 3π decay modes of the f^* with upper limits $2\pi/(K_1K_1+KK^*)<1$ and $3\pi/(K_1K_1+KK^*)<3$. We have found no evidence for a charged counterpart in the $\Sigma^{\mp}K\bar{K}\pi^{\pm}$ and $\Sigma^{\pm}K\bar{K}$ samples, constituting weak evidence in favor of $I=0$.

In summary, the existence of a resonance, with $M\approx 1500$ MeV/c^2 and $\Gamma\approx 85$ MeV/c^2, decaying into K_1K_1 and KK^*, appears reasonably well established, indicating $C=+1$ and $J^P=2^+$, 4^+, etc.

It is interesting to speculate on the role of the f^* within the framework of SU(3). If the f^* has the quantum numbers $J^P=2^+$ and $I=0$, it can be accommodated in a unitary nonet[17,18] with the $A_2(1320)$,[19] $K^*(1430$,[20,18] and $f(1250)$. The Gell-Mann–Okubo mass formula predicts a mass of 1470 MeV/c^2 for the isosinglet octet member. In view of the observed masses of the f and f^*, they apparently correspond to mixed singlet and octet states, as in the φ-ω case.[21] The mixing required to satisfy these mass values corresponds to an angle of ~20°, as compared to ~40° for the φ-ω case and ~10° for the η-η^* case. The magnitude of this mixing is sufficient to account for both the large value of the relative $2\pi/KK$ rate observed in f decay and the small value observed in f^* decay.[22]

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[1]G. W. London et al., Bull. Am. Phys. Soc. 10, 517 (1965).

[2]I. O. Skillicorn and M. S. Webster, Brookhaven National Laboratory Internal Report No. 8145 (unpublished). The pion contamination is estimated to be about 5%.

[3]W. J. Willis and H. Yuta, private communication, J. K. Kopp, Brookhaven National Laboratory Bubble Chamber Group, Internal Report No. F-68 (unpublished).

[4]We add the Σ^0 (but not the $\Sigma^{\pm}$) events to the Λ^0 events because (a) Λ^0-Σ^0 ambiguities (roughly 15% of the sample) make a separation difficult; and (b) Σ^0 events are not biased towards one isospin as are $\Sigma^{\pm}$ events.

[5]Since the K^0 cannot be distinguished from $\bar{K}^0$, both $M^2(Y^0K^0)$ and $M^2(Y^0\bar{K}^0)$ are plotted on the Dalitz plot. However, each of these points is counted as $\frac{1}{2}$ event in the Y^0K^0 projection. There is no ambiguity in the $K\bar{K}$ projection.

[6]We have estimated that about 7 to 10% of our 113 $\Lambda K\bar{K}$ events with one K visible $(K_1\to\pi^++\pi^-)$ are really $\Sigma^0K\bar{K}$ events which are underconstrained. This is determined by fitting unambiguous $\Sigma^0K\bar{K}$ where both K's are visible ignoring the information about one K. We thus have a contamination of about two events outside the φ region.

[7]See the compilation by A. H. Rosenfeld et al., Rev. Mod. Phys. 36, 977 (1964). See also J. Badier et al., Phys. Letters 16, 171 (1965); and G. A. Smith et al., in Proceedings of the Second Topical Conference on Resonant Particles, Ohio University, Athens, Ohio, 10-12 June 1965 (to be published).

[8]M. Goldhaber, T. D. Lee, C. N. Yang, Phys. Rev. 112, 1796 (1958).

[9]We include, in N_2, events with two visible K_1 decays and Λ seen or unseen. We ignore geometrical loss of the Λ and K_1 and take $\Gamma(\Lambda\to\pi^-+p)/\Gamma(\Lambda\to\pi^0+n)=\Gamma(K_1\to\pi^++\pi^-)/\Gamma(K_1\to\pi^0+\pi^0)=2$. See Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962, edited by J. Prentki (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 836.

[10]Only Λ events are used in this analysis. See reference 6.

[11]Our estimate of the background is 5 events. We have considered possible background interference and have found no significant effect.

[12]We ignore absorption effects. See K. Gottfried and J. D. Jackson, Nuovo Cimento 33, 309 (1964), for ex-

ample.

[13]About 8 events have been misidentified because of the Λ^0-Σ^0 ambiguity.

[14]For this purpose, the mass of the K^* was taken to be between 840 and 940 MeV/c^2.

[15]Due to the difference of 80 MeV/c^2 in mass, we do not believe that this enhancement is related to that observed by a CERN group at 1420 MeV/c^2; R. Armenteros et al., in Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963).

[16]The true mass of the resonance probably lies above 1500 MeV/c^2 due to the change in the Q value across the broad resonance. See J. D. Jackson, Nuovo Cimento 34, 1644 (1964). The estimate of the width is obtained from the K_1K_1 mass plot.

[17]R. C. Arnold, Phys. Rev. Letters 14, 657 (1965).

[18]L. M. Hardy et al., Phys. Rev. Letters 14, 401 (1965).

[19]G. Goldhaber et al., Phys. Rev. Letters 12, 336 (1964); S. U. Chung et al., Phys. Rev. Letters 12, 621 (1964); Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Letters 10, 226 (1964).

[20]N. Haque et al., Phys. Letters 14, 338 (1965).

[21]M. Gell-Mann and Y. Ne'eman, The Eightfold Way (W. A. Benjamin, Inc., New York, 1964), p. 11; J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962); S. Okubo, in Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, Ohio University, Athens, Ohio, 1963, edited by B. A. Munir and L. J. Gallahar (Ohio University Physics Department, Miami, Ohio, 1963), p. 193.

[22]After this paper was completed, we received a preprint in which similar but more extensive calculations concerning this 2^+ nonet are carried out. See S. Glashow and R. Socolow, following Letter [Phys. Rev. Letters 15, 329 (1965)].

BRANCHING RATIOS FOR DECAYS OF THE f^0, A_2, AND $K^*(1400)$ MESONS*

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Thus far, it has been possible to associate the low-mass baryon and meson resonances with SU(3) multiplets. In addition to providing a mass relation for members of a multiplet, the symmetry model relates their partial widths for decay into lower mass multiplets.[1] With the discovery of the $f'(1500)$,[2] it appears likely that the sequence[3] $f^0(M = 1253 \pm 10$ MeV; $\Gamma = 100 \pm 25$ MeV), $A_2(M = 1320 \pm 15$ MeV; $\Gamma = 85 \pm 10$ MeV), $K^*(M = 1410 \pm 10$ MeV; $\Gamma = 100 \pm 20$ MeV), and $f'(M = 1500 \pm 20$ MeV; $\Gamma = 100 \pm 25$ MeV) represents a nonet of $J^P = 2^+$ mesons. Because of the variety of decay modes accessible to these states, a comparison of available experimental data with the predictions based on SU(3) is of interest. Details of the calculations as well as references to other theoretical work on $J^P = 2^+$ mesons are given by Glashow and Socolow.[4]

To estimate the branching ratios for the f^0 and A_2, we used events produced in $\pi^- + p$ interactions at 3.2 BeV/c. Since this momentum is near threshold for $Y + K^*(1400)$, we obtained the branching ratios for $K^*(1400)$, using events produced at 3.9 and 4.2 BeV/c. The quantity of film used at each momentum is shown in Table I. Results on the branching fractions and cross sections are summarized in Table II. To facilitate comparison with other experiments, we indicate briefly the procedure used in the analysis; details will be published elsewhere.

The number of events corresponding to each decay mode and seen in our sample was estimated. (In most cases a smooth curve was drawn over the mass spectrum of the decay products to represent the background; the number of events above the curve and near the mass of the decaying particle was used.) This number was corrected for detection efficiency[5] (column 4 in Table II), and converted into cross-section units, by means of Table I. These values can then be directly compared to find the desired branching ratios.

Since the f^0, A_2, and $K^*(1400)$ are all produced peripherally in $\pi^- + p$ interactions, the low Δ^2 (four-momentum transfer squared) events

Table I. Summary of measured film used in estimating branching ratios.

Final state	Beam momentum (BeV/c)	Sample size (events/μb)
2 prongs	3.2	0.36
4 prongs	3.2	1.1
Events involving strange particles	3.2	8.0
Events involving strange particles	3.9 to 4.2	4.5