f, f', and A_2^0 Interference in $\pi N \to K^- K^+ N$ at 6 GeV/c*

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The Argonne effective mass spectrometer has been used for a high-statistics study of $\pi^-+p \to K^-+K^++n$ (110 000 events) and $\pi^++n \to K^-+K^++p$ (50 000 events) at 6 GeV/c. Comparison of the two reactions allows isolation of the interference between K^-K^+ states of differing isospin. We observe f-A_2^0, f'-A_2^0, and f-f' interferences in the Y_4^0 moment and find f' production to have a substantial contribution from some mechanism besides pion exchange. New values for the f' mass, width, and branching ratio into $\pi\pi$ are presented.

We report a study of tensor meson production using high-statistics measurements of the mass dependence of the K^-K^+ decay angular distribution moments in the reactions

$$\pi^-+p \to K^-+K^++n \quad (110\,000 \text{ events}), \tag{1}$$

$$\pi^++n \to K^-+K^++p \quad (50\,000 \text{ events}). \tag{2}$$

A previous experiment[1] on Reaction (1) showed the need for measurements sensitive to the isotopic spin I of the K^-K^+ system in order to understand the mass dependence of the Y_4^0 moment, which could not be described by interfering f and A_2^0 mesons alone. Comparison of Reactions (1) and (2) directly isolates $f-A_2^0$ and $f'-A_2^0$ interference terms. We demonstrate the presence of f' production for the first time in pion-induced reactions and provide new information on the $f'\pi\pi$ coupling (which, according to the Iizuka-Okubo-Zweig rule, should be highly suppressed). We also see f' production by a mechanism besides one-pion exchange (OPE).

Lipkin[2] has pointed out that if A_0 and A_1 are the amplitudes for production of the $I=0$ and $I=1$ K^-K^+ systems in Reaction (1), then the amplitude for Reaction (1) is A_0+A_1, while for the reaction $\pi^-+p \to \bar{K}^0+K^0+n$ the amplitude is A_0-A_1. By charge independence, this amplitude is the same as the one for Reaction (2). Symbolically we can write the cross sections for Reactions (1) and (2) as

$$\sigma^{\mp} \propto |A_0 \pm A_1|^2 = |A_0|^2+|A_1|^2 \pm 2\,\mathrm{Re}(A_0A_1^*),$$

where $\sigma \equiv (4\pi)^{1/2}d^2\sigma/dt\,dM$; M is the K^-K^+ effective mass; t is the four-momentum transfer to the recoil nucleon; and the superscripts $-$ and $+$ refer to Reactions (1) and (2), respectively. Summing the two cross sections eliminates the $A_0A_1^*$ interference term; taking the difference isolates that term. Similar relations hold for the various K^-K^+ decay moments; in this Letter, we confine our analysis to the Y_4^0 moment, which clearly exhibits the behavior of the D waves.[1] The contributions of the three tensor mesons to the Y_4^0 moment are, symbolically (the $\langle Y_l^m\rangle$ are defined in Ref. 1),

$$(\sigma^-+\sigma^+)\langle Y_4^0\rangle \propto |f|^2+|f'|^2+|A_2^0|^2+2\,\mathrm{Re}(ff'^*).$$

$$(\sigma^--\sigma^+)\langle Y_4^0\rangle \propto \mathrm{Re}(fA_2^{0*})+\mathrm{Re}(f'A_2^{0*}).$$

Data were taken at 6 GeV/c using the Argonne effective mass spectrometer[1,3]; the K^-K^+ mass range $M<1750$ MeV was analyzed for momentum transfers $-t<0.40$ GeV^2. Our apparatus is well suited to compare Reactions (1) and (2), which can be measured with only slight changes in the experimental method. Differences arise from the use of a deuterium target for Reaction (2) and from the presence of a charged recoil in Reaction (2). The latter difference caused little difficulty because the K^-K^+ pairs were measured with no attempt to detect the recoil nucleons. The experimental method is basically that used in Ref. 1 and in an earlier experiment to study $\rho-\omega$ interference,[4] which compared the reactions $\pi^-+p \to \pi^-+\pi^++n$ and $\pi^++n \to \pi^-+\pi^++p$; by charge symmetry, these reactions have identical cross sections for $\pi^-\pi^+$ masses away from the ω mass, allowing a check of the analytical methods for deuterium target data; agreement to better than 5% was found.

We have studied the tensor mesons in Reactions (1) and (2) by means of the Y_4^0 moment, which is known[1] to be dominated by the f meson for $M<1600$ MeV and $-t \lesssim 0.20$ GeV^2. There are in general ten D-wave amplitudes for each of the tensor mesons produced: five meson helicity states (m) for each of two nucleon helicity states (λ). Of the f, f', and A_2^0, only the f meson's production mechanisms are presently well understood[5,6]

TABLE I. Parameters determined from the fits described in the text. B_g is a Breit-Wigner for spin 3 (M_g =1713, Γ_g =228 MeV). [Note: The factors $2M$ in the $F_k(M)$ convert from $d^2\sigma/dt\,dM^2$ to $d^2\sigma/dtdM$; see, e.g., Appendix A of Ref. 8.] The error on a given parameter corresponds to the change which increases χ^2 by 1 when the remaining 11 parameters are reoptimized.

$F_k(M)/2M$	Q_k (μb/GeV) $-t$ range 0.08–0.20 (GeV^2)	$-t$ range 0.20–0.40 (GeV^2)
$\lvert B_f\rvert^2$	4.02 ± 0.14	1.04 ± 0.06
$\lvert B_{f'}\rvert^2$	0.08 ± 0.08	-0.06 ± 0.03
$\lvert B_A\rvert^2$	0.04 ± 0.07	-0.08 ± 0.03
$\mathrm{Re}(B_fB_{f'}{}^*)$	-1.40 ± 0.25	-0.08 ± 0.13
$\mathrm{Re}(B_fB_A{}^*)$	-0.39 ± 0.15	0.18 ± 0.06
$\mathrm{Re}(B_{f'}B_A{}^*)$	-0.59 ± 0.22	-0.09 ± 0.12
$\mathrm{Im}(B_fB_{f'}{}^*)$	0.24 ± 0.21	0.48 ± 0.16
$\mathrm{Im}(B_fB_A{}^*)$	0.43 ± 0.20	-0.36 ± 0.14
$\mathrm{Im}(B_{f'}B_A{}^*)$	-1.00 ± 0.30	-0.21 ± 0.07
$\lvert B_g\rvert^2$	6.68 ± 1.20	2.23 ± 0.38
$M_{f'}$ (MeV)	1506 ± 6	1510 ± 13
$\Gamma_{f'}$ (MeV)	70 ± 12	55 ± 19
χ^2/DF	49.1/44	52.4/44

(pion exchange dominates at small t); therefore, an analysis allowing for the effects of all ten amplitudes is needed. Specifically, let the mass dependence be contained in the D-wave Breit-Wigner decay amplitude[7] $B_i(M)$ for the ith tensor meson, while the production amplitude $A_i^{\lambda m}(t)$ contains the t dependence.[8] Then the total amplitude for production of a K^-K^+n final state (λ, m) is $D^{\lambda m}(M,t)=\sum A_i^{\lambda m}(t)B_i(M)$. The most general contribution of the three tensor mesons to $\sigma^-\langle Y_4^0\rangle$ is

$$\sigma^-\langle Y_4^0\rangle=\sum Q_k(t)F_k(M). \tag{3}$$

The nine mass functions $F_k(M)$ are given in Table I; the $Q_k(t)$ functions are linear combinations of terms of the form $\mathrm{Re}[A_i^{\lambda m}(t)A_j^{\lambda' m'}(t)^*]$ or $\mathrm{Im}[A_i^{\lambda m}(t)_j^{\lambda' m'}(t)^*]$.

With the addition to Eq. (3) of a tenth term, for the g meson contribution at high masses, we can fit[9] $\sigma^-\langle Y_4^0\rangle$ (and simultaneously $\sigma^+\langle Y_4^0\rangle$ with appropriate sign changes of several Q_k) for masses $M<1750$ MeV. Our data, shown as functions of M in broad t bands, are given in Fig. 1, along with curves from our fits to the data; resulting parameters are given in Table I. Each t interval was fitted independently, with $\sigma^-\langle Y_4^0\rangle$ and $\sigma^+\langle Y_4^0\rangle$ being fitted simultaneously with twelve free parameters: the coefficients of the nine D-wave terms, the g meson term, and the f' mass and width. A number of conclusions can be drawn.

f' mass and width.—$\sigma^-\langle Y_4^0\rangle$ exhibits a striking interference pattern near 1500 MeV due to interference of the narrow f' with the slowly varying high-mass tails of the f and A_2^0 Breit-Wigners. Our fits, which yield $M_{f'}=1506\pm5$ MeV, $\Gamma_{f'}=66\pm10$ MeV,[10] explicitly take interference effects into account in measuring the f' parameters. The currently accepted values[11] of $M_{f'}=1516\pm3$ MeV and $\Gamma_{f'}=40\pm10$ MeV may be *systematically* in error due to the neglect of interference effects[12] in previous f' studies using the reactions $\bar{K}+N\to\bar{K}+K+\Lambda/\Sigma^0$.

f'-A_2^0 interference.—This term, significant only for $-t>0.08$ GeV^2, is surprisingly large, since both f' and A_2^0 are produced with small

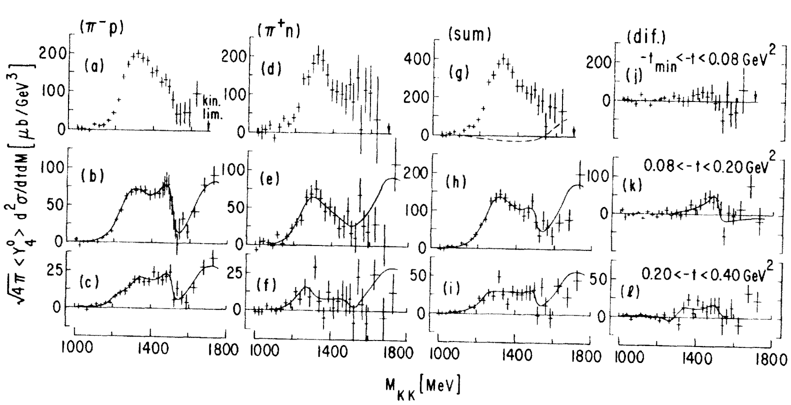

FIG. 1. $\sigma\langle Y_4^0\rangle$ in three t intervals for Reactions (1) and (2), their sum and their difference. The curves are the result of the fits described in the text. For $-t<0.08$ GeV^2, the arrow at 1690 MeV indicates the point at which $t_{min}=-0.08$ GeV^2. The moments are calculated in the t-channel frame. The dashed curve in (g) is an estimate of the P-F interference effects neglected in the fits.

cross sections in Reactions (1) and (2).

f-A_2^0 interference.—This term is significant only for $-t > 0.20$ GeV^2. The $f-A_2^0$ relative production phase of $63^{\circ\,+11^\circ}_{\ \ -15^\circ}$ implied by the fit for $-t > 0.20$ GeV^2 agrees with the prediction by Irving and Michael[8] of $\sim 70°$. For $-t < 0.20$ GeV^2, this term is much less important than f'-A_2^0 interference, despite the dominance of the f in the total cross section; therefore, f'(and A_2^0) production must have important contributions from amplitudes (λ, m) different from those responsible for f production.[13]

2^{++} nonet mixing angle and $f' \to \pi\pi$ branching ratio.—f-f' interference is significant for $-t < 0.40$ GeV^2. The crudely determined t dependence of $\mathrm{Re}(B_f B_{f'}{}^*)$ is compatible with an OPE production mechanism for that part of the f' amplitude coherent with the f amplitude. In the OPE-dominated range $0.08 < -t < 0.20$ GeV^2, the fit to $\sigma^{\mp}\langle Y_4^0\rangle$ implies an f-f' relative production phase of $170° \pm 10°$, consistent with OPE, which allows either 0° or 180°. The 180° value determines[2,14] the 2^{++} nonet mixing angle to be less than the ideal angle of 35.3°. The size of the f-f' interference term, relative to the $|f|^2$ term, implies $(f' \to \pi\pi)/(f' \to \mathrm{all}) = (1.40 \pm 0.55)\%$.[15] Note that obtaining the $f' \to \pi\pi$ branching ratio from f-f' interference requires data on both Reactions (1) and (2) to distinguish f-f' from f'-A_2^0 interference; Beusch *et al.*[16] proposed an upper limit of 0.9% in an analysis of the single reaction $\pi^- + p \to \bar{K}_s^0 + K_s^0 + n$ at 8.9 GeV/c. Their data are consistent with our data for Reaction (2). The suppression of $f' \to \pi\pi$ is analogous to suppression of $\varphi \to \rho\pi$: φ and f' are both $\lambda\bar{\lambda}$ states in the quark model and nonstrange decays are suppressed according to the Iizuka-Okubo-Zweig rule.[17] We emphasize that the conclusions about the $f' \to \pi\pi$ branching ratio and 2^{++} nonet mixing angle depend crucially on the assumption that *f-f' interference* for $-t < 0.20$ GeV^2 is due entirely to the OPE mechanism and that f production is dominated by OPE.

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[7]Our $B(M)$ are the $D(M)$ functions defined in Ref. 1. The masses and widths used are (in MeV): $M_f = 1279$, $\Gamma_f = 202$, $M_{A_2} = 1310$, $\Gamma_{A_2} = 104$. The f' mass and width were treated as free parameters.

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[9]The Q_k coefficients are averages over the finite t interval used. For $-t < 0.08$ GeV^2, $t_{\min}$ varies significantly with mass, hence the t-interval averaged over is mass dependent and we cannot do this type of analysis. We have omitted the effects of $P-F$ interference. Analysis of the Y_3^0 moment revealed no $I=0$ P wave (other than the φ meson), while the $I=1$ P wave was found to be just the $\pi\pi$ elastic P wave, corrected for the K^-K^+ decay phase space and coupling constant. In the F waves, the g meson ($I=1$) is expected to dominate over the $I=0$ $\omega(1670)$, so the only significant P and F waves both have isospin 1 and their interference contributes only to $\sigma_{\mathrm{sum}}\langle Y_4^0\rangle$. The estimated contribution for $-t < 0.08$ GeV^2 is shown in Fig. 1(g) as an example of the size of the neglected effect, which scales with t in the same way as the $|f|^2$ term since both the P wave and the g have OPE production mechanisms. For detailed discussion of P-wave effects, see A. J. Pawlicki *et al.*, ANL Report No. ANL-HEP-PR-76-44 (to be published).

[10]The absolute mass scale is known to ± 2 MeV and the effective mass resolution is ± 3 MeV at 1500 MeV.

[11]T. G. Trippe *et al.*, Rev. Mod. Phys. 48, S1 (1976).

[12]For example in $\bar{K} + N \to \bar{K} + K + \Lambda/\Sigma^0$, if f, f', and A_2^0 all had the same production phase, then the Breit-Wigner phases would give destructive f-f' and f'-A_2^0 interferences below the f' central mass, shifting the apparent f' peak to higher mass and narrower width.

[13]For example, Irving describes small t A_2^0 production as dominated by nucleon helicity nonflip $Z(J^{PC} = 2^{--})$ exchange. This is incoherent with nucleon helicity flip OPE f production amplitudes. See Ref. 8 and A. C. Irving, Nucl. Phys. B105, 491 (1976).

[14]H. J. Lipkin, private communication, and Nucl. Phys. B7, 321 (1968).

[15]The calculation follows that given in W. Beusch *et al.*, Phys. Lett. 60B, 101 (1975), except that the $|f'|^2$ term due to OPE is inferred from our f-f' interference term and the $f \to \bar{K}K$ branching ratio is taken from Ref. 1 as 0.031 ± 0.010.

[16]Beusch *et al.*, Ref. 15.

[17]I. Iizuka, Prog. Theor. Phys. Suppl. 37-38, 21 (1966); S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No. TH 412, 1964 (unpublished). See also the discussion in Beusch *et al.* (Ref. 15).