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f^0- A_2^0 Interference and the $f^0 \to K\bar{K}$ Branching Ratio*

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Interference in the $K\bar{K}$ decay mode of the f^0 and A_2^0 mesons is discussed in terms of the mass-matrix formalism. It is shown that the measurement of the $f^0 \to K\bar{K}$ branching ratio can be in error by an order of magnitude if interference is not properly accounted for. Data from π^+p and π^-p reactions at 18.5 GeV/c are used to determine the $(f^0 \to K\bar{K})/(f^0 \to \pi\pi)$ branching ratio R_{f^0} using the known $A_2 \to K\bar{K}$ branching ratio and assuming a value for the coherence factor. We find $9\% \le R_{f^0} \le 18\%$.

I. INTRODUCTION

The $f^0 \to K\bar{K}$ branching ratio has been a rather difficult quantity to measure for several reasons. First, the rate is small. But perhaps more important, interpretation of the $(K\bar{K})^0$ mass spectrum is complicated by the presence of the A_2^0. Since the A_2^0 and f^0 both have $J^P = 2^+$ and have masses which are close relative to their widths, interference in the $(K\bar{K})^0$ mass spectrum is expected to be strong.[1] The $A_2 \to K\bar{K}$ branching ratio itself can be determined without this complication by looking at the $K^\pm K^0$ decay mode since the A_2 has $I = 1$.

Previous experiments[2] have attempted to measure the $f^0 \to K\bar{K}$ branching ratio without taking interference into account. Here we describe the interference effects in detail and show that differences in the branching ratio of one order of magnitude can arise depending on whether the interference is constructive or destructive. This theory, based on the mass-matrix formalism, is developed in Sec. II. The experimental data are discussed in Sec. III and the data are fitted using the interference formalism in Sec. IV.

II. THEORY

If one observes a $K\bar{K}$ pair of invariant mass m from the decay of either an f^0 or an A_2^0, the amplitude for this observation is given, in the mass-matrix formalism,[3] by the matrix product

$$S(K\bar{K}) = (B_1 \quad B_2)P(m)\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}, \tag{1}$$

where B_1 and B_2 are the f^0 and A_2^0 production amplitudes and the T's are their $K\bar{K}$ decay amplitudes. The matrix P is given by

$$P(m)^{-1} = \begin{pmatrix} (m - m_1 + i\gamma_1) & \delta \\ \delta & (m - m_2 + i\gamma_2) \end{pmatrix}, \tag{2}$$

where m_1 and m_2 are the f^0 and A_2^0 masses, the γ_i's are their half-widths, and $\delta = -\langle f^0|M|A_2^0\rangle$ denotes the f^0-A_2^0 transition due to the electromagnetic mass operator. (Here δ must be electromagnetic because of the different isospins of the f^0 and the A_2.) Neglecting terms of order δ^2, Eqs. (1) and (2) yield

$$S(K\bar{K}) = B_1T_1b_1 + B_2T_2b_2 - \delta(B_1T_2 + B_2T_1)(b_1b_2), \tag{3}$$

where $b_i = 1/(m - m_i + i\gamma_i)$. The B's and T's in (3) are complex, and thus the expression is quite complicated in general. The magnitude of these amplitudes can be estimated from the f^0 and A_2^0 production cross sections and from their $K\bar{K}$ partial widths. Furthermore, an estimate of δ can be obtained from the work of Coleman.[4] These estimates show that the absolute magnitude of the third term in (3) is less than 5% of the magnitude of the first two terms, and thus we neglect the term linear in δ. Thus we can write

$$dN(K\bar{K})/dm = |B_1T_1b_1 + B_2T_2b_2|^2.$$

Note that the production and decay amplitudes now appear in pairs so that there is only one phase angle, ϕ (other than an arbitrary rotation), as a variable. Redefining constants, we can write this expression as

$$dN(K\bar{K})/dm = \pi^{-1}[A\gamma_1^{1/2}b_1 + B\exp(i\phi)\gamma_2^{1/2}b_2]^2$$
$$= A^2\pi^{-1}[\gamma_1^{1/2}b_1 + r\exp(i\phi)\gamma_2^{1/2}b_2]^2, \qquad (4a)$$

where $r^2 = B^2/A^2$ is the ratio of the intensity of the A_2^0 meson to the f^0 meson in the $K\bar{K}$ mass spectrum Here A, B, and r are real. The fraction of A_2^0 in the $K\bar{K}$ mass spectrum is given by

$$F = B^2/(A^2+B^2).$$

Noting that the terms in (4a) correspond to $I=0$ and 1 production of a neutral $K\bar{K}$ system, we can write the intensities for the K^+K^- and $K^0\bar{K}^0$ mass spectra, utilizing Clebsch-Gordan coefficients, as

$$dN(K^+K^-)/dm = \tfrac{1}{2}A^2\pi^{-1}[(c_1^2+d_1^2) + r^2(c_2^2+d_2^2) + 2r\alpha(c_1c_2+d_1d_2)\cos\phi - 2r\alpha(c_1d_2-c_2d_1)\sin\phi] \qquad (4b)$$

and

$$dN(K^0\bar{K}^0)/dm = \tfrac{1}{2}A^2\pi^{-1}[(c_1^2+d_1^2) + r^2(c_2^2+d_2^2) - 2r\alpha(c_1c_2+d_1d_2)\cos\phi + 2r\alpha(c_1d_2-c_2d_1)\sin\phi], \qquad (4c)$$

where c_i and d_i are the real and imaginary parts of the expression $\gamma_i^{1/2}b_i$, and we have introduced the coherence factor α where $0 \leqslant \alpha \leqslant 1$. We observe that, except for the case of $\alpha=0$, the individual K^+K^- and $K^0\bar{K}^0$ mass spectra depend on ϕ and that the f^0 and A_2^0 contributions interfere with opposite phases. Their sum is, however, independent of ϕ and of the coherence factor and is given by

$$dN(K\bar{K})/dm = A^2\pi^{-1}[(c_1^2+d_1^2) + r^2(c_2^2+d_2^2)]. \qquad (5)$$

To show how interference effects in the K^+K^- mass spectrum vary with ϕ and F, we define an enhancement factor E for the K^+K^- mass spectrum as

$$E(K^+K^-) = 2N(K^+K^-)/N(K\bar{K}), \qquad (6)$$

where the N's are calculated by integrating[5] Eqs. (4b) and (5) over m. Thus E is a factor representing the increase or decrease in the number of K^+K^- events as compared with the number calculated without considering interference effects. Figure 1 shows the dependence of E on F for several values of ϕ with $\alpha=1.0$. The enhancement approaches $E=2$ for $F=0.5$ and $\phi=30°$. This means that a $K\bar{K}$ branching ratio determined from K^+K^- events without considering interference effects could be high by a factor of two. On the other hand, $E \approx 0.2$ for $F=0.5$ and $\phi=-150°$ and would result in a branching ratio low by a factor of 5. Thus errors in the branching ratio as large as an order of magnitude can result if an incoherent sum of Breit-Wigner amplitudes b_i is assumed.

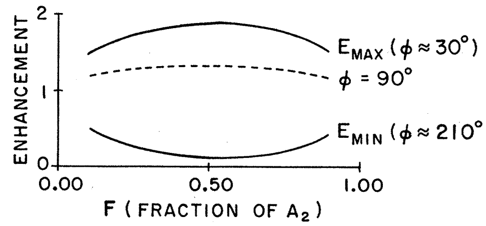

FIG. 1. The enhancement factor E as a function of F, the fraction of A_2^0 in the K^+K^- mass enhancement for several values of ϕ. These curves are for complete f^0-A_2^0 coherence ($\alpha = 1.0$).

III. EXPERIMENTAL PROCEDURE

The reactions which we have studied to determine the $K\bar{K}$ branching ratios are

$$\pi^\pm p \to pA_2^0\pi^\pm \qquad (7)$$

and

$$\pi^\pm p \to pf^0\pi^\pm \qquad (8)$$

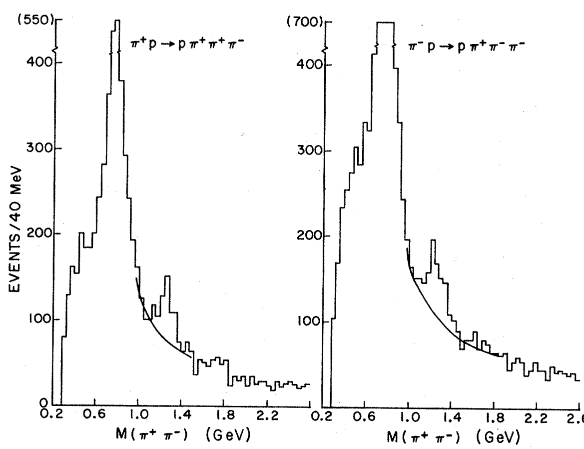

FIG. 2. The $\pi^+\pi^-$ effective-mass distributions from the reactions (a) $\pi^+p \to p\pi^+\pi^+\pi^-$ and (b) $\pi^-p \to p\pi^+\pi^-\pi^-$ at 18.5 GeV/c. The smooth curves are background estimates used to measure the f^0 signal.

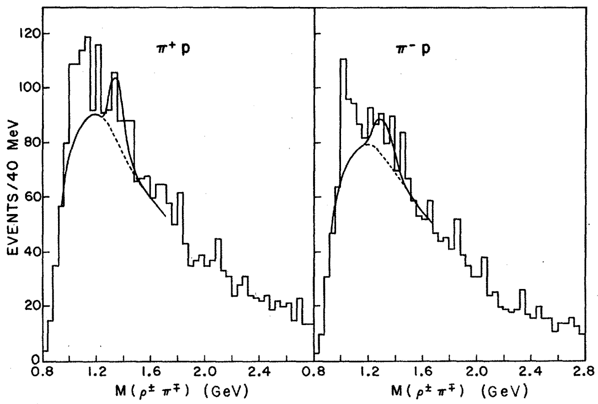

FIG. 3. The $\rho^{\pm}\pi^{\mp}$ effective-mass distributions from the reactions (a) $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$ and (b) $\pi^-p \to p\pi^+\pi^-\pi^-\pi^0$ at 18.5 GeV/c. The A_2^0 signal is estimated from the FAKE background curves shown.

at 18.5 GeV/c. The most copious decay modes of the A_2^0 and f^0 are $\rho\pi$ and $\pi\pi$, respectively, so the reactions in which we measure these decays are

$$\pi^{\pm}p \to p\pi^+\pi^{\pm}\pi^-\pi^0 \tag{9}$$

and

$$\pi^{\pm}p \to p\pi^+\pi^{\pm}\pi^-. \tag{10}$$

The procedures used in obtaining these event samples from 322 000 pictures taken in the Brookhaven 80-in. hydrogen bubble chamber are discussed elsewhere.[6-9]

Figure 2 shows the $\pi^+\pi^-$ effective-mass distributions for reactions (10). Clear f^0 signals can be seen for both π^+p and π^-p reactions, and cross sections have been determined for f^0 production followed by $\pi\pi$ decay using the smooth curves shown as background estimates. After correction to include the $\pi^0\pi^0$ decay mode, these cross sections are 153 ± 28 μb and 87 ± 9 μb for the π^+p and the π^-p reaction, respectively.

Figure 3 shows the $\rho^{\pm}\pi^{\mp}$ effective-mass distributions for reactions (9). The A_2^0 signals are much more difficult to observe than the f^0 signals in Fig. 2 because of a lower cross section and a higher background due in part to the large background included in the $\rho^{\pm}$ selection. [This selection was made by requiring $0.66 \leq M(\pi^{\pm}\pi^0) \leq 0.86$ GeV.] The background curves shown are based on events generated by a Monte Carlo program. Estimating the cross sections for A_2^0 production followed by $\rho\pi$ decay from the excess of events between 1.20 and 1.36 GeV and correcting for $\rho\pi$ events excluded by the ρ selection, we find values of 21.5 ± 5.0 μb and 13.5 ± 2.8 μb for the π^+p and π^-p reactions, respectively.

To measure the $K\bar{K}$ decay rates of the A_2^0 and f^0 produced in reactions (7) and (8), we have isolated[10]

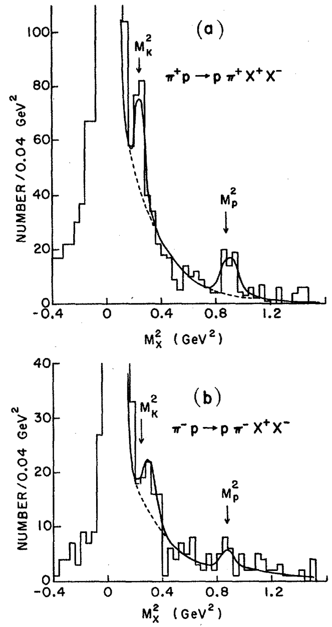

FIG. 4. The distribution of M_X^2 (see text) for (a) π^+p and (b) π^-p 4-prong interactions at 18.5 GeV/c for events with an identified proton. The background and the $K\bar{K}$ and $p\bar{p}$ signals are shown by the smooth curve.

the reactions

$$\pi^{\pm}p \to pK^+K^-\pi^{\pm} \tag{11}$$

in our 18.5-GeV/c experiment. To determine the cross sections for these reactions we have used an unfitted energy-momentum technique similar to that used by Ehrlich *et al.*[11] for the study of the reactions $\pi^{\pm}p \to pp\bar{p}\pi^{\pm}$. These reactions are of the generic type

$$\pi^{\pm}p \to \pi^{\pm}pX^+X^-, \tag{12}$$

where X^+X^- represents a particle-antiparticle pair. Using the measured momenta of the particles

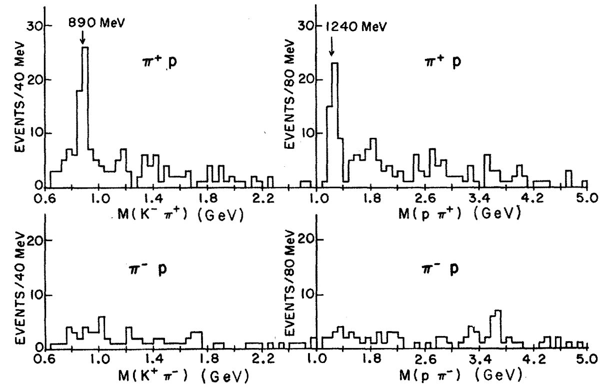

FIG. 5. The $K\pi$ and $p\pi$ effective-mass distributions for the reactions $\pi^{\pm}p \to pK^+K^-\pi^{\pm}$ at 18.5 GeV/c.

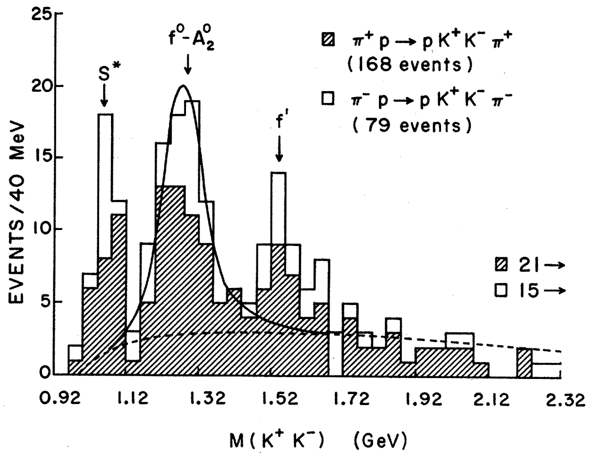

FIG. 6. The K^+K^- effective-mass distributions for the reactions $\pi^+p \to pK^+K^-\pi^+$ and $\pi^-p \to pK^+K^-\pi^-$. The curve is described in the text.

we first impose a momentum-conservation constraint to eliminate reactions involving neutral particles. Energy conservation is then used to determine the mass M_X of the X^+ and X^- particles.

The distributions of $M_X{}^2$ for the π^+p and the π^-p interactions with an identified proton are shown in Fig. 4. Apart from the dominant $m_\pi{}^2$ peak, we observe significant peaks at the $m_K{}^2$ and $m_p{}^2$ values. The cross sections for $K\bar{K}$ and $p\bar{p}$ are significantly higher for π^+p than for π^-p interactions. To determine the $p\bar{p}$ and $K\bar{K}$ signals a detailed study was made of the background.[10] After correction for background and for selection inefficiency we obtain cross sections of 51.5 ± 13.5 μb and 27.0 ± 9.5 μb for the π^+p and π^-p reactions (11), respectively.

In Fig. 5 are shown the $K\pi$ and $p\pi$ effective-mass distributions for events of reactions (11) selected by kinematic fitting. Resonance production is particularly strong for the π^+p data as evidenced by K^{*0} and N^{*++} peaks. Detailed analyses of these peaks show that they correspond to 34% and 17% of this reaction, respectively. The statistics for the π^-p reaction are too small for us to make any strong statement other than to note that resonance production is less prominent.

Figure 6 shows the K^+K^- mass distributions for reactions (11). The dashed curve is peripheral phase space and is normalized to the data at the high end of the mass spectrum. The three peaks seen in the data correspond to $S^*(1060)$ production, $f'(1520)$ production, and a broad enhancement between 1160 MeV and 1360 MeV corresponding to the f^0-A_2^0 mass region. We will concentrate on the latter peak in order to determine the $f^0 \to K\bar{K}$ branching ratio. This peak corresponds to a cross section of 10.9 ± 3.1 μb above background for the π^+ data and to 6.1 ± 2.6 μb for the π^- data.

IV. THE $f^0 \to K\bar{K}$ BRANCHING RATIO

If interference effects are ignored, we can determine the branching ratios $R_{A_2} = (A_2 \to K\bar{K})/(A_2 \to \rho\pi)$ and $R_{f^0} = (f^0 \to K\bar{K})/(f^0 \to \pi\pi)$ directly from the data in Sec. III if we assume a definite fraction of A_2^0 in the f^0-A_2^0 peak shown in Fig. 6. Figure 7 shows these ratios as a function of the A_2^0 fraction F and corresponds to the case with coherence factor $\alpha = 0.0$. We have included corrections for the $K^0\bar{K}^0$ decay modes in computing the ratios in Fig. 7.

In order to include interference effects, we must assume a value of α and then determine r^2 and ϕ in expression (4b). The values of r^2 (or F) and ϕ will correspond to an enhancement factor E (Fig. 1) which can then be incorporated into R_{A_2} and R_{f^0} in Fig. 7 to yield the correct branching ratios. To determine r^2 and ϕ, a maximum-likelihood fit to the K^+K^- mass spectrum (Fig. 6) in the region $1120 \le M(K^+K^-) \le 1400$ MeV was done using expression (4b). For $\alpha = 1.0$, the best values of the parameters are $F = 1\%$ and $\phi = 11°$. This fit is shown in Fig. 6 and in Fig. 8(a). In Fig. 8(a) are shown 1-, 2-, and 3-standard-deviation contours in the F-ϕ plane. Because the uncertainties in ϕ

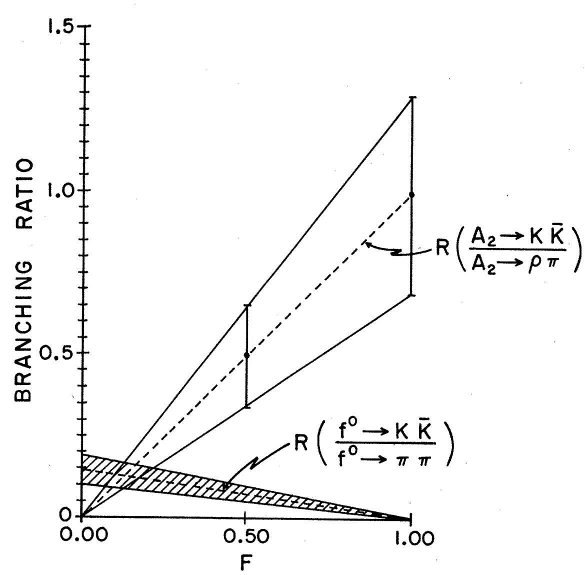

FIG. 7. The values of $R_{A_2} = (A_2 \to K\bar{K})/(A_2 \to \rho\pi)$ and $R_{f^0} = (f^0 \to K\bar{K})/(f^0 \to \pi\pi)$ as a function of F if interference effects are ignored.

TABLE I. Maximum-likelihood fits assuming $3\% \le R_{A_2} = (A_2 \to K\bar{K})/(A_2 \to \rho\pi) \le 12\%$.

Data sample	Coherence factor α	$R_{f^0} = \dfrac{f^0 \to K\bar{K}}{f^0 \to \pi\pi}$	Phase angle ϕ (rad)	F
All	1	$9\% \le R_{f^0} \le 18\%$	$-1.8 \le \phi \le 2.0$	$2.5\% \le F \le 7.5\%$
All	0.5	$11\% \le R_{f^0} \le 18\%$	Any value allowed	$3\% \le F \le 13\%$
All	0	$11.7\% \le R_{f^0} \le 14.2\%$	Not applicable	$4\% \le F \le 20\%$
$\pi^+ p$	1	$12\% \le R_{f^0} \le 24\%$	$-2.7 \le \phi \le -0.6$	$3\% \le F \le 9\%$

and F from the fit are large, we have not attempted to determine both R_{A_2} and R_{f^0} from our data, but we assume R_{A_2} to be known and then determine R_{f^0}, ϕ, and F. (As discussed earlier R_{A_2} can be measured unambiguously from charged-A_2 decays.) For R_{A_2} we use the A_2 branching fractions recently reported by Barnham *et al.*[12] These branching fractions correspond to $R_{A_2} = (7.7 \pm 3.9)\%$. Contours of R_{A_2} in the F-ϕ plane are shown in Fig. 8(b). [Contours of R_{f^0} are given in Fig. 8(c) for ready reference.] The intersection of the 1-standard-deviation area of Fig. 8(a) and the $3\% \le R_{A_2} \le 12\%$ area[13] of Fig. 8(b) is shown in Fig. 8(d). From this figure we obtain the results, $9.0\% \le R_{f^0} \le 18\%$, $-1.8 \le \phi \le 2.0$ rad, and $2.5\% \le F \le 7.5\%$.

In order to study the sensitivity of these results on α, we have performed similar analyses for $\alpha = 0.5$ and $\alpha = 0.0$. These results are shown in Table I along with the results for $\alpha = 1.0$. It is interesting to note that the value of R_{f^0} is rather insensitive to α.

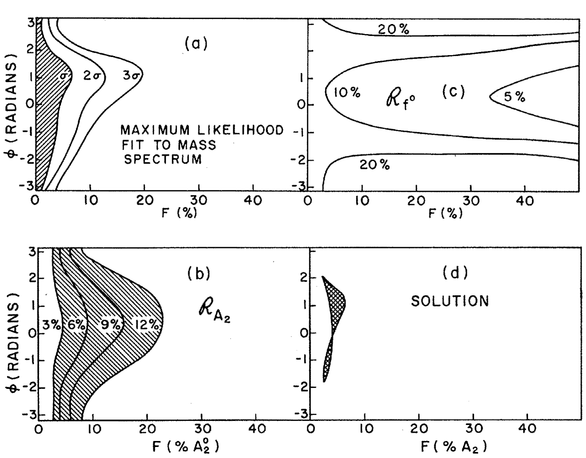

FIG. 8. (a) Contours of equal likelihood in the ϕ-F plane for function (b) fitted to the data of Fig. 6 in the f^0-A_2^0 region. (b) Contours of R_{A_2} in the ϕ-F plane determined from the data. (c) Contours of R_{f^0} in the ϕ-F plane determined from the data. (d) Best solution obtained by superimposing the acceptable regions from (a) and (b).

Finally, since it is possible that ϕ is different for the π^+ and the π^- data, we have used the π^+ data sample by itself to determine R_{f^0}. This result, for $\alpha = 1$, is also given in Table I. We note that this result is consistent with the results for the combined data.

V. CONCLUSIONS

We observe a peak in the K^+K^- mass spectrum between 1.16 and 1.4 GeV which can be interpreted as being due to the K^+K^- decay mode of the f^0 and A_2^0 mesons. These channels can interfere. Analysis of the spectrum yields an $(f^0 \to K\bar{K})/(f^0 \to \pi\pi)$ ratio of $9\% \le R_{f^0} \le 18\%$ if we assume that the A_2 is a simple (nonsplit) 2^+ resonance with a $K\bar{K}/\rho\pi$ branching ratio between 3% and 12%, and that the coherence is maximal. Although the relative phase between the f^0 and A_2^0 and the fraction of A_2^0 depend on the coherence factor α, the branching ratio is relatively independent of α.

We show that the combined K^+K^- and $K^0\bar{K}^0$ mass spectrum would not be affected by interference effects. We suggest that a higher statistics experiment with a capability of measuring both K^+K^- and $K^0\bar{K}^0$ mass spectra would be very informative in studying the branching ratios. The phase determination using the individual mass spectra as a function of mass could be important regarding the question of splitting of the A_2 meson.

ACKNOWLEDGMENTS

Our initial interest in the f-A_2 problem was stimulated by the work by Dr. John Marraffino who studied the K_1K_1 system as part of his thesis.[14] We are pleased to acknowledge the cooperation of the 80-in. bubble chamber group and of the Alternating Gradient Synchrotron personnel at Brookhaven National Laboratory. The assistance of W. L. Rickhoff and R. L. Erichsen was invaluable in the experiment. The hard work of the Notre Dame scanning and measuring staff is greatly appreciated. Several discussions with Dr. K. Lassila were very helpful.

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[1]In this paper, we have ignored possible A_2 splitting. Recent experiments [see, e.g., P. Weilhammer *et al.*, Bull. Am. Phys. Soc. 16, 610 (1971); S. J. Lindenbaum *et al.*, *ibid.* 16, 610 (1971); and B. Gottschalk *et al.*, *ibid.* 16, 610 (1971)] have presented evidence against splitting, leading to more controversy on this point. We point out that, if the A_2 is split, this analysis must be modified to include the correct phase dependence of the A_2, or, with sufficient statistics, could be modified to *determine* this phase dependence.

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Measurement of the Ratio of the Axial-Vector to the Vector Coupling in the Decay $\Sigma^- \rightarrow ne^- \bar{\nu}$†

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From a sample of 393 Σ^- β decays, we have selected 63 events in which a proton recoil from a neutron interaction in the chamber is observed. From the measured values of the electron-neutrino angle we conclude that for the $\Sigma^- \rightarrow ne^-\bar{\nu}$, $|g_A/g_V| = 0.29^{+0.28}_{-0.29}$. This result is obtained from a maximum-likelihood calculation which includes the effect of a well-understood background of 27 ± 6 events contained in our sample.

I. INTRODUCTION

The ability of the Cabibbo[1] theory to correlate all data on leptonic decays of hadrons has prompted a series of experiments to improve the experimental information on such decays. In particular, on the basis of the rates alone for leptonic decays, the theory can predict the magnitude of the vector and axial-vector coupling, thus inviting more direct comparisons with observations.

Methods by which the relative amounts of such couplings can be determined in the leptonic decay of a spin-$\frac{1}{2}$ baryon into three fermions are well known.[2,3] For the decay of unpolarized baryons and when the polarization of the decay baryon is not observed, the electron-neutrino correlation or equivalently the baryon recoil spectrum is very sensitive to the type of interaction, but not the relative sign of the two couplings. In the case of the decay $\Sigma^- \rightarrow n + e^- + \bar{\nu}$, the presence of two neutral particles in the final state makes the determination of the relevant correlation very difficult. However, since it is easier to produce a large number of unpolarized Σ^- hyperons than polarized