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James S. Lindsey and Gerald A. Smith

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I. SPIN ANALYSIS

Because the ϕ has a low Q, the neutral-to-charged mass difference of the K meson has considerable effect on the relative angular-momentum barrier for $\phi \to K^+K^-$ and $K_1^0 K_2^0$. Including a small Coulomb correction, Schlein et al.[4] and London et al.[5] have calculated

$$R = \frac{\Gamma(\phi \to K_1^0K_2^0)}{\Gamma(\phi \to K_1^0K_2^0)+\Gamma(\phi \to K^+K^-)} = \begin{cases} 0.39 & \text{for } J = 1 \\ 0.26 & \text{for } J = 3 . \end{cases} \tag{1}$$

These groups find they are in conflict with J = 3 by approximately 2 and 2.5 standard errors, respectively (4.6 and 1.2% probability), whereas in both cases their results are consistent with J = 1 within one standard error ($\geq$ 32% probability). This certainly constitutes strong evidence for the J = 1 hypothesis. We measure $R = 0.46 \pm 0.04$, which is within 1.5 standard errors of J = 1 and 4.7 standard errors ($< 10^{-2}$% probability) removed from J = 3.

II. "$\phi\omega$" MIXING AND $\phi \to \rho\pi$ AND $\eta\gamma$

Glashow[3] has shown that the matrix elements for the processes ϕ (or ω) $\to \pi\gamma$ or $\eta\gamma$ may be conveniently expressed in terms of the mixing angle θ ($\approx$ 40 deg from the $\phi\omega$ mass splitting) and the $\omega\rho\pi$ and $\phi\rho\pi$ couplings. Using the results of Barmin et al.[6] on the lower limit for $\omega \to \pi\gamma$ compared to $\omega \to \pi^+\pi^-\pi^0$, and the results of Flatté et al.[7] on the upper limit for $\omega \to$ (all neutrals) compared to $\omega \to \pi^+\pi^-\pi^0$, we have $\Gamma(\omega \to \pi\gamma) \approx 0.9$ MeV. Using this as input, and including a p^3 phase-space dependence, Glashow predicts

$$\Gamma(\omega \to \eta\gamma) \approx 0.002\,(1 - 5\epsilon)^2 \text{ MeV} \tag{2a}$$

$$\Gamma(\phi \to \pi\gamma) \approx 2.1\,\epsilon^2 \text{ MeV} \tag{2b}$$

and

$$\Gamma(\phi \to \eta\gamma) \approx 0.26\,(1 + 0.2\epsilon)^2 \text{ MeV}, \tag{2c}$$

where ϵ is the ratio of the $\phi\rho\pi$ to $\omega\rho\pi$ couplings.[8] Consequently, a value of ϵ is sufficient to complete the predictions.

We now discuss our results for $\phi \rightarrow \rho\pi$ or $\eta\gamma$, deferring comparison of our results with Glashow's predictions until the Conclusions.

A. $\phi \rightarrow \rho\pi$

This experiment has yielded a sample of 16 000 events which have a best fit to $\Lambda\pi^+\pi^-\pi^0$. Of these, a large fraction result from the intermediate state $Y_1^*(1385)\ \pi\pi$. The sample of events under investigation, therefore, includes only those having no $\Lambda\pi$ combination with an effective mass between 1345 and 1425 MeV. In addition, we have selected only events with low momentum transfer, $\Delta^2_{p,\Lambda} \leq 0.8\ (\mathrm{BeV/c})^2$, and events in which any $\pi\pi$ combination is in the ρ band (650 to 850 MeV). One potential difficulty with this measurement results from the substantial ambiguity between $\Lambda 3\pi$ and ΛK^+K^- (and others). Of those events that qualify as ΛK^+K^-, 65% also pass as $\Lambda 3\pi$. These events have been assigned to the ΛK^+K^- hypothesis, a four-constraint fit compared to a one-constraint fit for $\Lambda 3\pi$. However, one should consider the possibility that true ΛK^+K^- events, which for some unknown reason may not give an acceptable fit to ΛK^+K^-, still fit $\Lambda 3\pi$. Very likely the resultant momentum unbalance for the ΛK^+K^- hypothesis in such an event would be small and assigned to the neutral in a $\Lambda 3\pi$ fit. In addition, the 3π effective mass would be close to the K^+K^- value. Thus, a small number of these dominantly ϕ production events could produce a false peak in the 3π mass spectrum in the vicinity of the ϕ. Specifically, a study of those events that pass <u>both</u> ΛK^+K^- and $\Lambda 3\pi$ has shown that the laboratory momentum of the π^0 was <u>always</u> less than 20 MeV/c, whereas the π^+ and π^- laboratory momenta exhibited considerably less tendency to peak near zero.

In Fig. 1 we have plotted the laboratory momentum spectra for (a) the π^0 from $\Lambda 3\pi$ events that do <u>not</u> also fit ΛK^+K^- and which have their 3π mass in the ϕ region (1000 to 1040 MeV) and (b) the combined π^+ and π^- for the same events. The most striking feature of Fig. 1a is the sharp peaking of the spectrum near zero [to be compared with the not so nearly peaked combined π^+, π^- spectrum of Fig. 1b[9]]. In addition to ΛK^+K^-, other channels should be suspect at this point. For example, the peripheral nature of the final states $\Sigma^0 K^+K^-$ and $\Sigma^0\pi^+\pi^-$ results in the photon from Σ^0 decay being emitted preferentially backwards in the production center of mass, thus giving a small laboratory momentum for the π^0 in a $\Lambda 3\pi$ fit to the event. In addition, $\Lambda\pi^+\pi^-$ tends (infrequently) to be ambiguous with $\Lambda 3\pi$. Events that fit one or more of these latter three mentioned channels (but not as well as $\Lambda 3\pi$) are cross-hatched in Fig. 1a and exhibit a definite peaking near zero. Lastly, each event in Fig. 1a was fitted to $\Lambda^0(\Sigma^0)K^+\pi^-$ hypotheses including a contaminant π^- in the beam; events that fit successfully such hypotheses are shaded and also tend to group near zero. Therefore, we feel that it is sufficient to reject most of the possible contamination in the $\Lambda 3\pi$ channel by removing all events with a π^0 laboratory momentum less than 50 MeV/c. The 3π mass spectrum for events that satisfy our established criteria is shown in Fig. 2. Figure 2a shows the fitted 3π effective-mass distribution which assumes that the missing neutral is a π^0, and Fig. 2b shows the unfitted mass spectrum (taken from measured track quantities) for the same events. The most striking feature of both graphs is the peak due to the $\eta(959) \rightarrow \pi^+\pi^-\gamma$ decay. The small upward shift of its mass in the fitted data results from the erroneous assumption that the neutral mass is that of a π^0. The two graphs are consistent with each other in the appearance of a slight enhancement near 1020 MeV. Evaluation of the background near the ϕ is made difficult by the proximity of the $\eta(959)$, and the curve shown on the figure is at best an estimate. We measure the ϕ signal to be 30±12 events;

however, we must allow for a possible systematic error of ±15 events on the central value. In order to correct for events subtracted from our sample due to the cuts on $\Lambda\pi$ effective mass and π^0 momentum, this number must be multiplied by a correction factor of 2.1, which has been determined by a Monte Carlo generation of events of the type $K^- + p \rightarrow \Lambda^0\phi$, $\phi \rightarrow \rho\pi$.[9] Table I summarizes our data on this and other decay modes.

B. $\phi \rightarrow \eta\gamma$

The evidence for or against the existence of the decay mode $\phi \rightarrow \eta\gamma$ was necessarily displayed in a previous article dealing with a search for the C-violating mode $\phi \rightarrow \omega\gamma$.[1] We observe no evidence for $\phi \rightarrow \eta\gamma$, and measure its signal to be 0 ± 14 events (see Table I).

III. CONCLUSIONS

(a) Our data confirm, with substantially greater statistical accuracy than previous experiments using this method, the assignment of spin one for the ϕ.

(b) Glashow has suggested that the magnitude of ϵ may be inferred from the ratio $\Gamma(\phi \rightarrow 3\pi)/\Gamma(\omega \rightarrow 3\pi)$. If we combine our $\phi \rightarrow 3\pi$ branching ratio[10] with the known width of 3.3 MeV for the ϕ,[11] then we have $\Gamma(\phi \rightarrow 3\pi) \approx 0.5$ MeV. Along with the known width[11] of the $\omega \rightarrow 3\pi$ mode (10.6 MeV), this leads to $|\epsilon| \approx 0.2$. Therefore, we have $\Gamma(\phi \rightarrow \eta\gamma) \approx 0.26$ MeV, or a branching ratio of approximately 8% of the total. Our experimental results (0 ± 8%) are clearly in agreement with Glashow's prediction. One should note, however, from Eq. (2c) that the rate for $\phi \rightarrow \eta\gamma$ is not a particularly sensitive function of $|\epsilon|$ and in itself does not constitute a very strong test of the theory. Nevertheless, it is interesting to note that this value of $|\epsilon|$ leads to predictions of extremely small values (≤ 0.1 MeV) for the rates of $\omega \rightarrow \eta\gamma$ or $\phi \rightarrow \pi\gamma$. The former has been confirmed by experiment;[7] the latter still awaits experimental test.

The authors wish to acknowledge Professor George Trilling for helpful discussions in regard to elimination of background from our $\Lambda 3\pi$ sample, and Professor Luis Alvarez for his support and encouragement in this experiment.

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8. We are unable to shed any light on the decay $\phi \to \pi\gamma$ because such events would be included among an immense background in the vee-zero-prong topology. To the best of our knowledge no information exists on this particular mode.
9. To check that our pion laboratory momentum distributions of Fig. 1 are close to what one would expect from kinematics alone, we have Monte Carlo generated 750 fake events of the type $K^- + p \to \Lambda^0\phi^0$, $\phi^0 \to \rho^0\pi^0$, using the form of our observed ϕ production center-of-mass angular distributions and assuming that the ϕ and ρ decay isotropically in their own rest frames. These events (dashed curve) show a tendency for peaking at low momentum, consistent with the data of Fig. 1b but not at all consistent with the marked peaking of 1a.

10. We may obtain a branching ratio for $\phi \rightarrow \pi^+\pi^-\pi^0$ by scaling our $\rho\pi$ numbers by 1.25, correcting for the $\pi\pi$ mass cut. This gives 110±74 events, corresponding to a 14±10% branching ratio of the total. We are aware of two other experiments that have published results bearing on the $\rho\pi$ branching ratio: (1) London et al. (Ref. 5) give $\Gamma(\phi \rightarrow \rho\pi)/\Gamma(\phi \rightarrow K\bar{K}) = 0.30\pm0.15$, to be compared with our value of 0.14±0.08. (2) Badier et al. give $\Gamma(\phi \rightarrow \pi^+\pi^-\pi^0)/\Gamma(\phi \rightarrow K\bar{K}) = 1.04\pm0.30$, to be compared with our value of 0.17±0.12 [J. Badier, M. Demoulin, J. Goldberg, B. Gregory, C. Pelletier, A. Rouge, M. Ville, R. Barloutaud, A. Leveque, C. Louedec, J. Meyer, P. Schlein, A. Verglas, D. Holthuizen, W. Hoogland, J. Kluyver, A. Tenner, Physics Letters 17, 337 (1965)]. It appears that our results compare favorably with those of London et al., but are in much poorer agreement with those of Badier et al.

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Table I. Summary of ϕ-decay data for $\Delta^2_{p,\Lambda} \leq 0.8$ (BeV/c)^2.

Decay mode	Observed events	Correction for neutral decay	Correction for scan. and meas.	Corrected events	Branching ratio (% total)
$\phi \rightarrow K^+K^-$	252±16	1.0	1.4±0.05	353±26	48±4
$K_1^0K_2^0$	167±13	1.5	1.2±0.09	301±33	40±4
$\rho\pi$	30±20[c]	2.1[a]	1.4±0.05	88±59	12±8[d]
$\eta\gamma$	0±14	3.1[b]	1.4±0.05	0±61	0±8

a. This factor corrects for phase space due to the $\Lambda\pi$ mass cut and removal of events with a π^0 momentum less than 50 MeV/c.

b. This factor corrects for η decays into "all neutral" modes not observed in this experiment.

c. This error represents our estimated systematic error in calculating phase space, folded in with the statistical error.

d. See footnote 10.

FIGURE LEGENDS

Fig. 1. Laboratory momentum distribution of (a) π^0 and (b) combined π^+ and π^- from events that best fit $\Lambda\pi^+\pi^-\pi^0$ but not ΛK^+K^-, and have a three pion effective mass in the range 1000 to 1040 MeV. Events with any $\Lambda\pi$ combination in the range 1345 to 1425 MeV or any $\pi\pi$ combination outside the range 650 to 850 MeV have been removed. The data are only at low momentum transfer, $\Delta^2_{p,\Lambda} \leq 0.8(\text{BeV/c})^2$. The crosshatched events are those that also fit some other hypothesis (except ΛK^+K^-), but not as well as $\Lambda 3\pi$. The shaded events give an acceptable fit to an incident pion hypothesis. The dashed curve in (b) is the result of our Monte Carlo generation of 750 $\Lambda\phi$ events, using the known ϕ-production angular distribution and assuming that the ϕ and ρ decay isotropically in their own rest frames.

Fig. 2. Effective mass of the three pions for events that fit $\Lambda\pi^+\pi^-\pi^0$ from (a) fitted data and (b) unfitted data, at low momentum transfer only. Events in the $Y_1^*(1385)$ band or outside the ρ band have been removed, as well as events with a laboratory π^0 momentum ≤ 50 MeV/c.

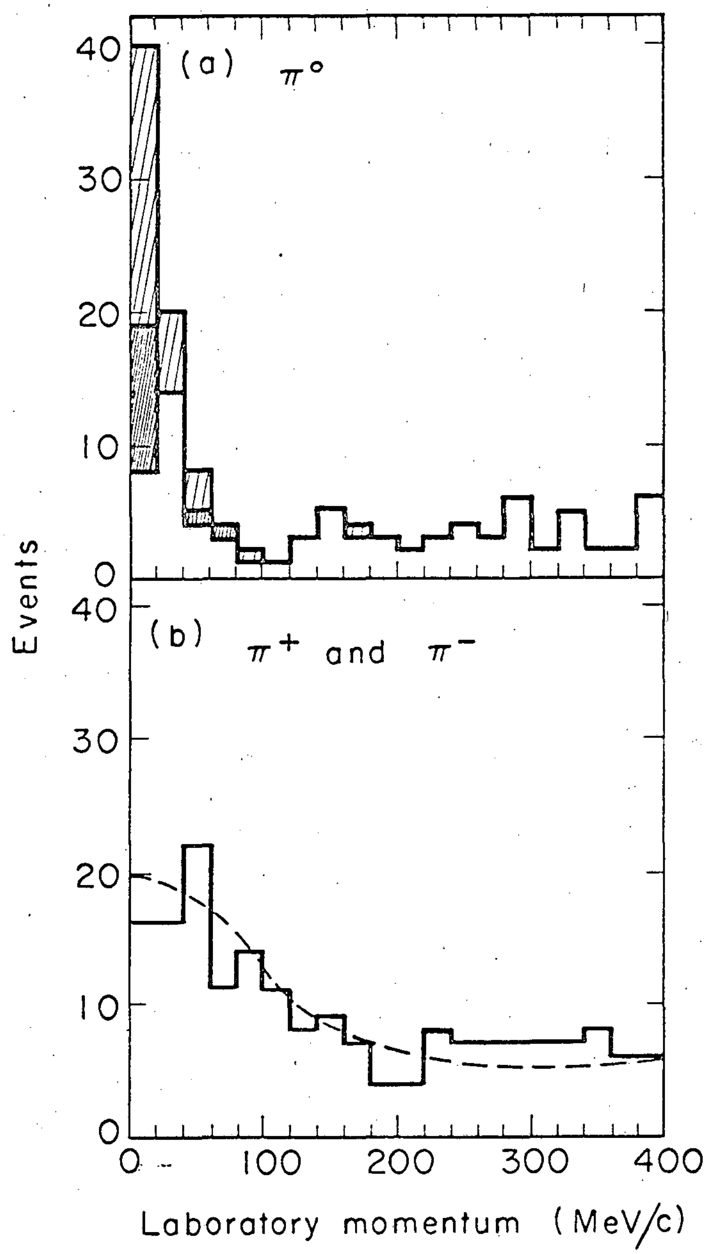

Fig. 1

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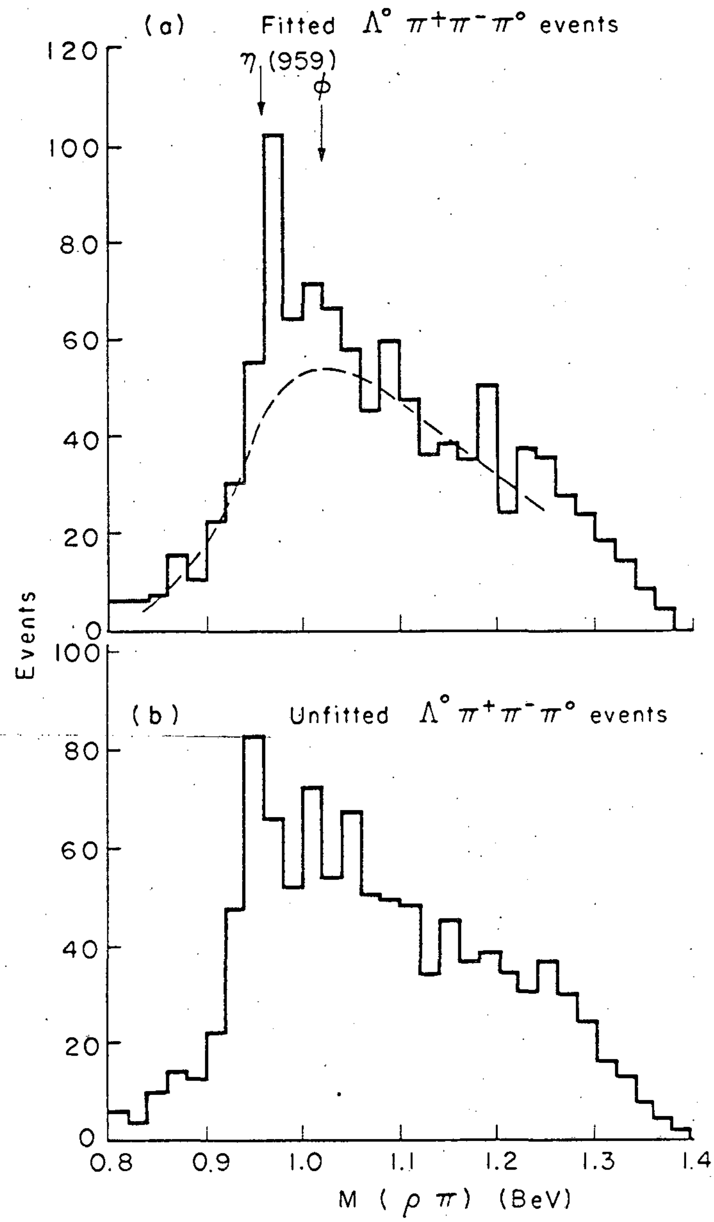

Fig. 2

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