SEARCH FOR φ-MESON PRODUCTION IN 3.7-GeV/c π^--p COLLISIONS*

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In analyzing high-energy K^--p collisions in a hydrogen bubble chamber, two groups have reported[1] evidence for a sharp resonance in the $K\bar{K}$ mass spectrum from the final state $\Lambda^0+K+\bar{K}$. This resonance has been labeled the φ meson. It has a mass of 1019 MeV and a width of about 1 MeV. The evidence indicates that its quantum numbers are $J^{PG}=1^{--}$ and that it is an isotopic singlet ($T=0$). These are the same quantum numbers that are presently assigned to the ω meson (which has a mass of 782 MeV), and at first sight one might expect the rate of $\varphi\rightarrow\pi^+\pi^-\pi^0$ (which is the principal mode of ω decay) to be somewhat larger[2] than the rate of $\varphi\rightarrow K\bar{K}$. Experimentally, however, the 3π rate of the φ seems to be anomalously low,[1] implying that the physical coupling constant $G_{\rho\varphi\pi}$ is small compared to $G_{\rho\omega\pi}$. This might also lead to a small production rate for φ's as compared with ω's in π-p collisions, as suggested by Glashow.[3]

In this paper we present results which set an upper limit of about 0.012 for the ratio of the rates

$$(\pi^- + p\rightarrow\pi^- + p+\varphi)/(\pi^- + p\rightarrow\pi^- + p+\omega),$$

indicating that this ratio is, indeed, very small. In the first part of the paper we present the data which pertain to this ratio, and in the second part we try to interpret the processes by which the ω-production reaction may take place.

(I) The φ and ω production rates. – We have made an exposure at the Brookhaven AGS in the BNL 20-inch hydrogen chamber subjected to 3.7-GeV/c π^- mesons. The exposure consisted of 60 000 pictures. The analysis of about two thirds of these is included in the present data. Some preliminary results on the various reactions that are observed have been given previously.[4]

We have analyzed about 2600 four-prong reactions using the Brookhaven TRED-KICK programs and the University of Michigan IBM-7090 computer. Of these 2600 events, there were 724 which fit the reaction

$$\pi^- + p\rightarrow\pi^- + p+\pi^+ +\pi^- +\pi^0 \qquad (1a)$$

with a chi-square probability of at least 0.02, and in which the bubble densities, as estimated by a physicist, were consistent with the predicted values. Of the 729 events, 104 were ambiguous with the $\pi^-\pi^+\pi^+\pi^-n$ final state. We have included these ambiguous events in this analysis, since the unambiguous $\pi^-\pi^+\pi^+\pi^-n$ events are only about one-half as numerous as the unambiguous $\pi^-p\pi^+\pi^-\pi^0$ events. There were also 170 events which fit both Reaction (1a) and the reaction

$$\pi^- + p\rightarrow\pi^- + p+\pi^+ +\pi^- . \qquad (2)$$

We have not included these events in the present sample, since Reaction (2) is a four-constraint ($4C$) kinematic fit, whereas Reaction (1a) is a one-constraint ($1C$) fit. It has been our experience with this experiment that those events which are ambiguous between $4C$ and $1C$ fits, and in which the ambiguity can be resolved by looking at the bubble density, almost invariably turn out to be the $4C$ case. Furthermore, the (presumably fake) $\pi^+\pi^-\pi^0$ invariant mass spectrum from these latter 170 events has an entirely different appearance than that of 729 "good" events, and, in particular, shows no evidence of an ω peak.

For the 729 events of type (1a), we have plotted the distribution of the invariant mass (M^*) of the $\pi^+\pi^-\pi^0$ combinations in Fig. 1(a). There are two combinations for each event. The distribution follows the Lorentz-invariant momentum space (phase space) quite well except for a pronounced peak at about 790 MeV which is due to ω production via the reaction

$$\pi^- + p\rightarrow\pi^- + p+\omega,\quad \omega\rightarrow\pi^+ +\pi^- +\pi^0. \qquad (1b)$$

Of the 207 events which fall in the interval (790 ± 40) MeV, we estimate that about 120 of them are in the ω peak above phase space, corresponding to a production cross section of (0.45 ± 0.07) mb.

We have searched for φ-meson production by studying the reaction

$$\pi^- + p\rightarrow\pi^- + p+K^+ +K^- . \qquad (3a)$$

Out of the sample of 2600 four-prong events, there were 20 which satisfied all the criteria for Reaction (3a). The distribution of the M^* of the K^+K^- from these events is shown in Fig. 1(b). There is only one event in the interval 1010 to 1030 MeV and, in fact, no other event is located such that 1019 MeV falls within three standard deviations of its M^*. We conclude that the rate of the reac-

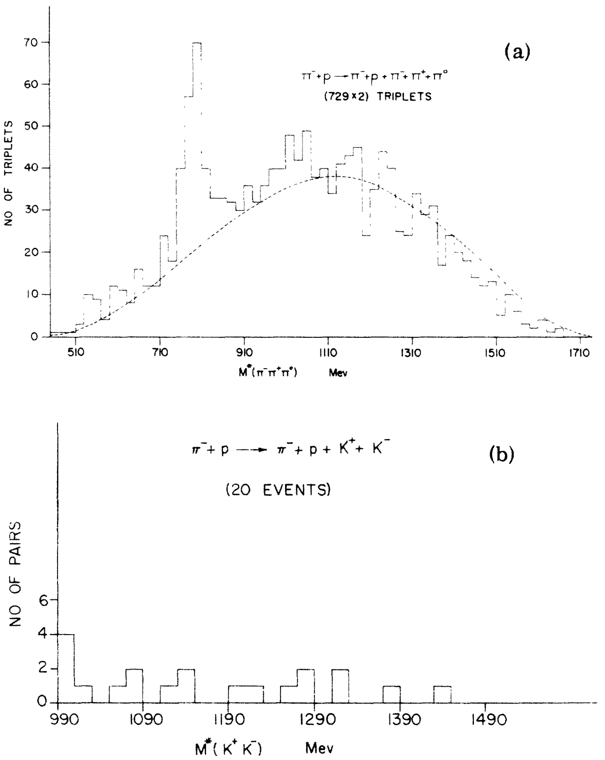

FIG. 1. (a) Distribution of effective mass of $\pi^+\pi^-\pi^0$ triplets from Reaction (1a). The dashed curve represents the phase space. (b) Distribution of the effective mass of K^+K^- pairs from Reaction (3a).

tion

$$\pi^- + p \to \pi^- + p + \varphi, \quad \varphi \to K^+ + K^- \qquad (3b)$$

is about equal to or less than 1/120 of the rate for (1b).

If we now take into account the measured branching ratios $(\omega \to \pi^+\pi^-\pi^0)/(\text{all }\omega) = 0.84$,[5] and $(\varphi \to K^+K^-)/(\varphi \to K^+K^- + K_1^0K_2^0) = 0.57$,[6] and make the assumption that all of the φ decay is into the $K\bar{K}$ channel,[7] then we obtain an upper limit for the ratio of the production cross sections

$$\frac{\sigma(\pi^- p \to \pi^- p\varphi)}{\sigma(\pi^- p \to \pi^- p\omega)} \lesssim (0.84/0.57)(1/120) = 0.012.$$

We remark that the corresponding ratio of phase space for these two reactions is 0.55.

(II) Interpretation of the ω-production reaction.—We now consider the 207 events ("ω events") of type (1a) in which the M^* of the $\pi^+\pi^-\pi^0$ system is inside 790 ± 40 MeV. Some possible one-particle exchange diagrams which could give rise to ω production are shown in Fig. 2. If the φ has the same

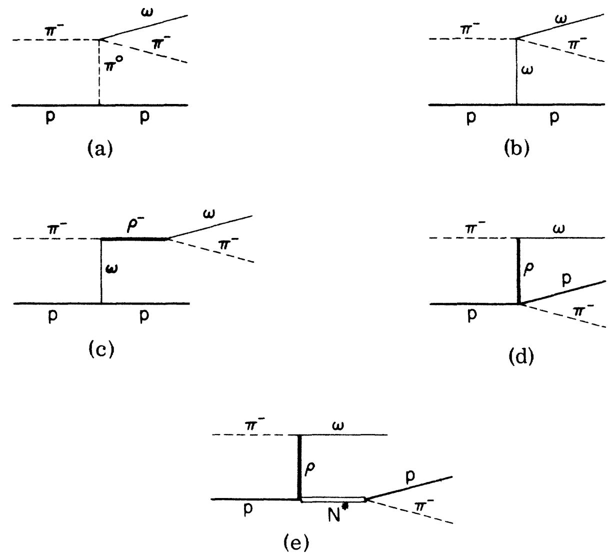

FIG. 2. One-particle-exchange diagrams for the reaction $\pi^- + p \to \pi^- + p + \omega$.

quantum numbers as the ω, then φ production could occur through similar diagrams. In order to test our events for diagram 2(a), we have plotted α_{TY}, the Treiman-Yang angle,[8] in Fig. 3. This is defined as the angle between the plane of the incoming and outgoing proton and the plane of the outgoing π^- and ω, all taken in the rest system of the incoming π^-. The diagram 2(a) would lead to an isotropic distribution in α_{TY}. The top histogram in Fig. 3(a) clearly indicates that at least some of our 207 events are not going via one-pion

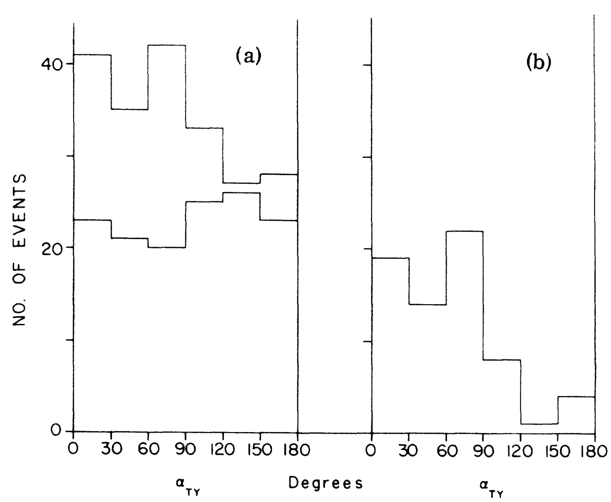

FIG. 3. Treiman-Yang angle distributions. (a) Upper histogram represents all 207 "ω events." Lower histogram is for ω events outside the N^* region. (b) For events inside the N^* region.

exchange.

When the extra π^- is emitted at the nucleon vertex, G-parity conservation forbids one-pion exchange diagrams. Therefore we have looked for N^* production, for example, by diagram 2(e). The results (Fig. 4) show a significant bump at $M^*(\pi^-p) = 1700$ MeV which is probably due to the 1688-MeV, $T = 1/2$ resonance previously observed in π-p total cross-section measurements.[5] It appears that in about 25% of our ω productions, the outgoing π^--p form this N^* state. The events with $M^*(\pi^-p)$ inside 1700± 80 MeV show a large anisotropy in α_{TY} [Fig. 3(b)], whereas the "outside" events show no significant anisotropy. However, the "outside" events fail to satisfy another criterion for one-pion exchange, namely, the distribution in $\cos\theta$, where θ is the angle that the outgoing ω makes with respect to the incoming π^-, all taken in the center-of-momentum system (c.m.s.) of the outgoing $(\pi^-\omega)$. Conservation of isotopic spin, angular momentum, and parity at the $\pi + \pi \to \omega + \pi$ vertex requires that the distribution of $\cos\theta$ should go to zero when $\cos\theta = \pm 1$, in disagreement with our results, as shown in Fig. 5.

Figure 5, in fact, seems to show a $1 + \cos^2\theta$ distribution which should occur if the reaction were going through ω exchange with an intermediate ρ [Fig. 2(c)].[9] Unfortunately, the distribution of $\cos\gamma$ (where γ is the angle between the normal to the ω decay plane and the incoming π^-)[10] does not support this conclusion. Our observed $\cos\gamma$ distribution is essentially isotropic, whereas the prediction for Fig. 2(c) is $1 + \cos^2\gamma$ (for one-pion exchange it should be $1 - \cos^2\gamma$). Hence, no sin-

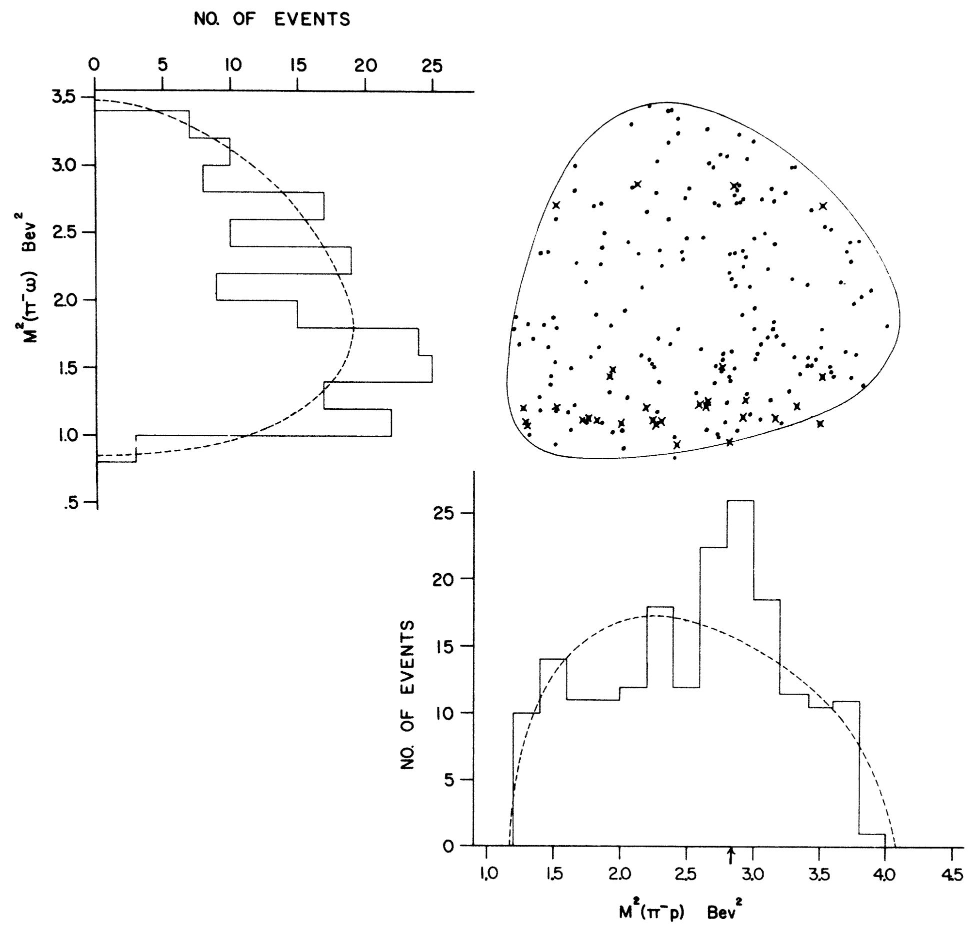

FIG. 4. Dalitz plot of $M^2(\pi^-\omega)$ vs $M^2(\pi^-p)$ for the state $\pi^-p\omega$ with total energy 2.80 GeV. The enclosed area represents the allowed kinematical region. A pure phase distribution would result in a uniform population of the plot. The crosses represent 15 "double-ω" events in which both $\pi^+\pi^-\pi^0$ triplets fall within the ω region. Such an event has a single value of $M^2(\pi^-\omega)$ and two values for $M^2(\pi^-p)$. The crosses have been counted as one-half event each in the projections onto the $M^2(\pi^-\omega)$ and $M^2(\pi^-p)$ axes. The arrow on the $M^2(\pi^-p)$ axis represents $(1.688\text{ GeV})^2$. The dashed curves represent the area of the Dalitz plot projected onto the two axes and normalized to the total number of events in the histograms.

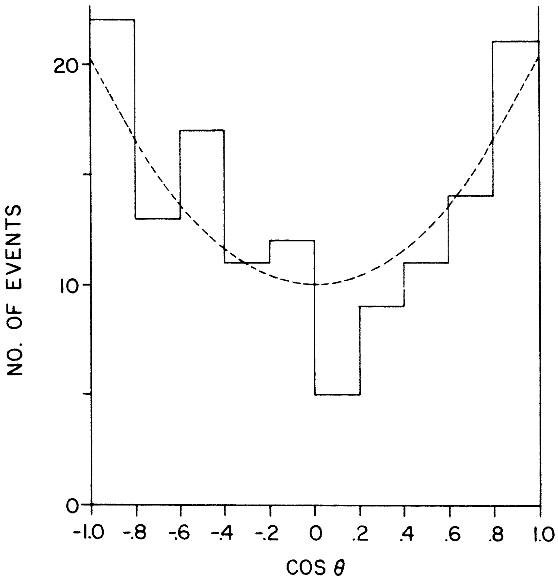

FIG. 5. Distribution of the cosine of the ω-production angle in the $(\omega\pi^-)$ c.m.s. for those events with $M^*(\pi^-p)$ outside the N^* region. The dashed curve represents $1+\cos^2\theta$ normalized to the number of events in the histogram.

gle diagram of Fig. 2 appears predominant, although a combination of them is certainly not excluded. We remark that none of these angular distributions is significantly changed if we make a subtraction of the incoherent background under the ω peak by examining the adjacent regions.

Summary.—We have found an upper limit of about 0.012 for the ratio of the reaction rates $(\pi^- + p \to \pi^- + p + \varphi)/(\pi^- + p \to \pi^- + p + \omega)$ at an incident π^- momentum 3.7 GeV/c. Provided one can explain why the contributions from higher order processes (such as diagrams involving $K, \bar{K}$ lines) are less than this limit, it is perhaps tempting to try to interpret this result as being due to $G_{\rho\varphi\pi}{}^2/G_{\rho\omega\pi}{}^2 \lesssim$ a few percent. Such a situation could arise within the framework of "φ-ω mixing" in which it is speculated that the observable ω and φ are linear combinations of two "bare" particles which are members of a vector-meson octet and singlet in the SU_3 scheme.[2] The suggestion[3,11] is that perhaps the mixing parameter and bare couplings are such that the physical coupling constant $G_{\rho\varphi\pi}$ is small compared to $G_{\rho\omega\pi}$.

We find that in about 25% of the ω-production reactions (1b), the outgoing π^-p form a N^*(1688 MeV) and that at our energy the Reaction (1b) does not go predominantly through one-pion exchange. It should be pointed out that this latter conclusion is in disagreement with that reached by another group[12] who studied the same process at 4.0 GeV.

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[5]M. Roos, Rev. Mod. Phys. 35, 314 (1963).

[6]We use the average of the values quoted in reference 1.

[7]Connolly et al. (reference 1) quote a value for the branching ratio $(\varphi \to \rho + \pi)/(\varphi \to K + \bar{K}) = 0.35 \pm 0.2$. If we take this into account (and neglect any other possible 3π modes), we should increase our upper limit for the production cross-section ratio to $1.35 \times 0.012 = 0.016$. However, if our small φ-production rate can be interpreted as being due to $G_{\rho\varphi\pi} \approx 0$, then the strong decays of the φ, other than $K\bar{K}$, may be practically absent. As for electromagnetic decays, such as $\varphi \to \pi^+\pi^-$ or $\pi^0\gamma$, if the φ width is really of order 1 MeV (as suggested in reference 1), these can probably also be neglected.

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[9]Marc Ross (private communication).

[10]Following the arguments of H. Stapp [University of California Radiation Laboratory Report No. 8096 (unpublished)], we have computed the ω decay-plane normal by transforming the momenta of the three π's first from the laboratory into the $\omega\pi_{out}^-$ c.m.s. and then into the ω c.m.s. To obtain $\cos\gamma$, this normal is then dotted into the direction which we obtain by transforming the momentum of the incoming π^- from the laboratory into the $(\omega\pi_{out}^-)$ c.m.s.

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