PHYSICAL REVIEW D VOLUME 13, NUMBER 1 1 JANUARY 1976

$\phi(1020) \to \rho(770)\pi$ decay*

G. R. Kalbfleisch and R. C. Strand
Brookhaven National Laboratory, Upton, New York 11973

J. W. Chapman
University of Michigan, Ann Arbor, Michigan 48104
(Received 2 June 1975)

The $\phi(1020) \to 3\pi$ decay appears to be dominated by $\rho\pi$ final states.

The decay $\phi \to 3\pi$ occurs with a branching fraction of 0.16 ± 0.02,[1] including an unknown fraction of $\rho\pi$ final states. The experimentally observed narrow width[2] of the ψ[2-4] has been the subject of intense theoretical debate. The arguments frequently use properties of the $\phi(1020)$ directly or by analogy.[5,6] In particular, Takasugi and Oneda[7] argue that the widths of the ψ and ϕ can be compatible in the "charmonium" model only if $(\phi \to \rho\pi)/(\phi \to 3\pi)$ is less than 10%. This conclusion may be modified by SU_2-breaking effects. Others[5] argue that "asymptotic freedom"[8] takes care of the discrepancy in comparing the ψ and ϕ widths. More information on $\phi(1020)$ decay modes, presented here, should help to clarify such discussions.

These data on the decay modes of the $\phi(1020)$ are taken from a study of 2.18-GeV/c K^-p interactions in the BNL 31-inch liquid hydrogen bubble chamber. The reactions of interest are

$$K^-p \to \Lambda K_S(K_L) \qquad (1)$$

$$\to \Lambda K^+K^- \qquad (2)$$

$$\to \Lambda \pi^+\pi^-\pi^0 , \qquad (3)$$

where K_S denotes $K^0 \to \pi^+\pi^-$ and (K_L) denotes a computed missing K^0. There are only a few events of the type

$$K^-p \to \Lambda K_S K_S , \qquad (4)$$

so that it is correct to label the missing K^0 as (K_L^0) in reaction (1). Events which fit reactions (1) and (2) are dominated by

$$K^-p \to \Lambda\,\phi(1020) . \qquad (5)$$

The reactions

$$K^-p \to \Lambda \pi^+\pi^- \qquad (6)$$

$$\to \Sigma^0\pi^+\pi^- \qquad (7)$$

can feed background into reaction (3). The sample of events for reaction (3) is obtained by accepting all events that fit reaction (3) having the laboratory momentum of the reconstructed π^0 greater than 50 MeV/c and which do not fit reaction (2) or

$$K^-p \to \Sigma^0 K^+K^- . \qquad (8)$$

The overlap with reaction (6) is eliminated by the 50-MeV/c π^0 cut, and the overlap with reaction (7) is partially eliminated by this cut. Since reaction (7) cannot yield ω, η, or ϕ signals when fitted to reaction (3), the overlapping background will decrease the statistical significance of any signals but will not cause any systematic bias. Less than 6% of events of a highly constrained nature, such as reaction (2) or (6), fail to have acceptable fits. However, the 50-MeV/c π^0 cut will eliminate most of these events from the sample for reaction (3). Thus the three decay modes of the ϕ observed in the selected samples for reactions (1)–(3) have losses which are small, comparable, and less than the statistical uncertainty of the experiment.

Optimal mass resolution and signal-to-noise ratio in reaction (3) are obtained by a further cut in momentum transfer squared, between the proton and Λ, to $-t_{p,\Lambda} \leq 0.5$ GeV^2. This cut accepts 60% of all ϕ's with $-t_{p,\Lambda} < 0.8$ GeV^2, for which the scanning criteria of this experiment are unbiased. Figures 1(a), 1(b), and 1(c) present the mass spectra of the selected events for reactions (1), (2), and (3), respectively. A fit[9] of a resolution-broadened ϕ signal plus a linear background has been made to the data of Fig. 1(c) above a mass of 0.988 GeV in order to determine the number of $\phi \to \pi^+\pi^-\pi^0$ decays. Below 0.988 GeV, the tail of the $\eta' \to \rho^0\gamma$ events, misidentified as $\pi^+\pi^-\pi^0$, can be seen. The number of ϕ decays found from the data of Fig. 1(a), 1(b), and 1(c) are 133 ± 12 K_SK_L, 321 ± 18 K^+K^-, and 195 ± 62 $\pi^+\pi^-\pi^0$, respectively. Correcting for the branching fraction $(K_S \to \pi^+\pi^-)/(K_S \to \text{all}) = 0.688$ and assuming a fraction 0.03 ± 0.01 for other decay modes of the $\phi(1020)$,[1] the branching fractions of the $\phi(1020)$ to $K^0\bar{K}^0$, K^+K^-, and 3π are found to be 0.27 ± 0.03, 0.44 ± 0.05, and 0.26 ± 0.07, respectively. These are in moderate agreement with the accepted values[1] of 0.346 ± 0.022, 0.466 ± 0.025, and 0.158 ± 0.015, respectively. Also, the ratio of $\phi \to K_SK_L$

to $\phi \to K^+K^-$ is expected to be 0.67, owing to angular momentum barriers and kaon mass differences for the small phase space available. Our ratio is 0.60 ± 0.06 as compared to the "world average" value of 0.74 ± 0.06. The average mass of $\phi \to K_S K_L$ and $\phi \to K^+K^-$ from Figs. 1(a) and 1(b) is $\bar{M} = 1019.7 \pm 0.5$ MeV. The width $\Gamma = 3.8 \pm 0.5$ MeV of the $\phi \to K^+K^-$ was reported previously.[9] These results also agree with the accepted values

$$M = 1019.7 \pm 0.3 \text{ MeV} \quad \text{and} \quad \Gamma = 4.2 \pm 0.2 \text{ MeV}.$$

The fit to Fig. 1(c) determines the mass of $\phi \to \pi^+\pi^-\pi^0$ to be 1016.4 ± 2.6 MeV; the observed width is due entirely to the resolution of $\Gamma_R \sim 20$ MeV (FWHM). A shift in the observed mass and width values in $\phi \to 3\pi$ decay as compared to $K\bar{K}$ can be expected owing to the different variations of the phase space. A calculation using different Breit-Wigner parameterizations[10] indicates that differences $\delta M = M(\phi \to 3\pi) - M(\phi \to K\bar{K}) \simeq -2$ to 0 MeV and $\delta\Gamma = \Gamma_{\text{obs}}(\phi \to 3\pi) - \Gamma_{\text{obs}}(\phi \to K\bar{K}) \simeq 0$ to $+1$ MeV can exist. The $e^+e^- \to \phi \to K\bar{K}$ or 3π experiment of Augustin *et al.*[11] sees a possible $\delta M = -1$ or -2 MeV. Thus all the parameters of our $\phi(1020)$ data are consistent with other data.

The question remains whether $\phi \to 3\pi$ is dominated by $\rho\pi$ final states, as might be expected *a priori* owing to the spin-isospin structure of the $J^P = 1^-$ 3π matrix element. Prior bubble-chamber experiments[12] made ρ selections in order to observe $\phi \to 3\pi$. However, such a selection will accept a large fraction ($\gtrsim 0.5$) of the $\phi \to 3\pi$ phase space whether or not $\rho\pi$ final states are present. These earlier experiments also had ≤ 60 events each. The e^+e^- storage-ring experiments[13] have not analyzed substructure in the 3π decay.

Since the signal-to-noise ratio is ~1:3 [Fig. 1(c)], a meaningful Dalitz plot cannot be shown. Instead, in order to examine substructure, the Dalitz plot corresponding to a 3π system of mass M_{123} is divided into parts that are interior to a triangle inscribed inside the Dalitz boundary and parts that are exterior to it. The mass squared, M_{123}^2, of three particles is related to the mass squared of the three diparticle subsystems (M_{ij}^2) as follows:

$$M_{123}^2 = (M_{12}^2 + M_{13}^2 + M_{23}^2) - (m_1^2 + m_2^2 + m_3^2)\,, \qquad (9)$$

where the m_i's are the rest masses of each of the three particles. For a 3-pion subsystem, ignoring the mass difference between charged and neutral pions,

$$M_{12}^2 + M_{13}^2 = M_{123}^2 - M_{23}^2 + 0.057 \text{ GeV}^2\,. \qquad (10)$$

At the boundary of the Dalitz plot, where, e.g., $M_{23}^2 = \text{minimum} = (m_2 + m_3)^2 = 0.076 \text{ GeV}^2$, $M_{12}^2 = M_{13}^2$, so that the M^2 value describing the sides of the inscribed triangle is

$$M_{\text{triangle}}^2 = \tfrac{1}{2}(M_{123}^2 - 0.019) \text{ GeV}^2\,. \qquad (11)$$

At the mass of the $\omega(783)$ ($M_{123}^2 = 0.613$ GeV^2), $M_{\text{triangle}}^2 = 0.297$ GeV^2 (545 MeV), and at the mass of the $\phi(1020)$ ($M_{123}^2 = 1.040$ GeV^2), $M_{\text{triangle}}^2 = 0.511$ GeV^2 (714 MeV). The maximum dipion mass for an $\omega(783)$ is 643 MeV, and that for a ϕ is 880 MeV. Thus ω's contain $\rho(770)$ only virtually (the tail of Breit-Wigner distribution far below the ρ peak), whereas ϕ can contain $\rho\pi$ states explicitly. The M_{triangle}^2 cut for the ϕ in fact falls below the ρ peak. It divides the ρ Breit-Wigner distribution into a fraction 0.31 below and 0.69 above. In Fig. 2(a) and 2(b), the data of Fig. 1(c) are shown separated into the exterior and interior regions of the Dalitz plot, respectively, according to Eq. (11). Qualitatively, (a) the $\omega(783)$ is split about evenly in the two plots, (b) the $\eta'(958)$ (misidentified as 3π at 965–970 MeV is mostly in the exterior region (since the η' decays to $\rho^0\gamma$), and (c) the ϕ is predominantly in the exterior region, indicating that $\phi \to 3\pi$ is dominated by $\rho\pi$ final states.

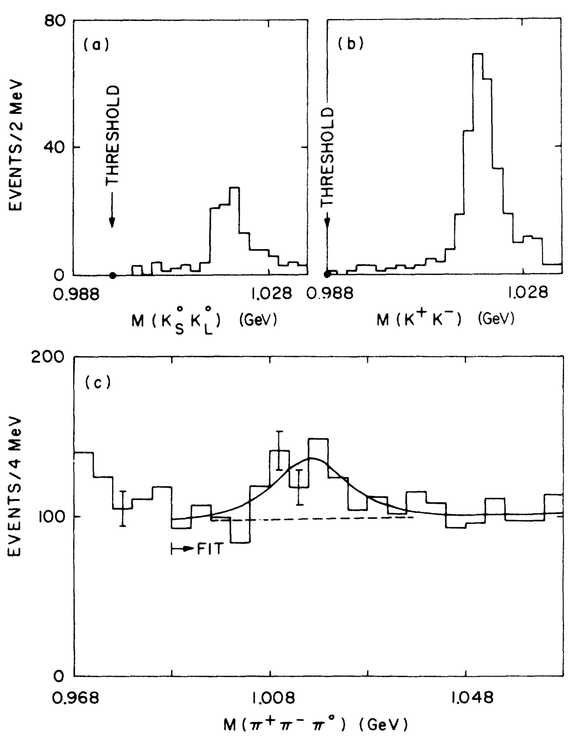

FIG. 1. Mass distributions of (a) $K_S K_L$ events, (b) K^+K^- events, and (c) $\pi^+\pi^-\pi^0$ events. Threshold is marked in (a) and (b). The solid fitted curve in (c) is discussed in the text (ϕ mass is free). The dashed curve is the estimated background level.

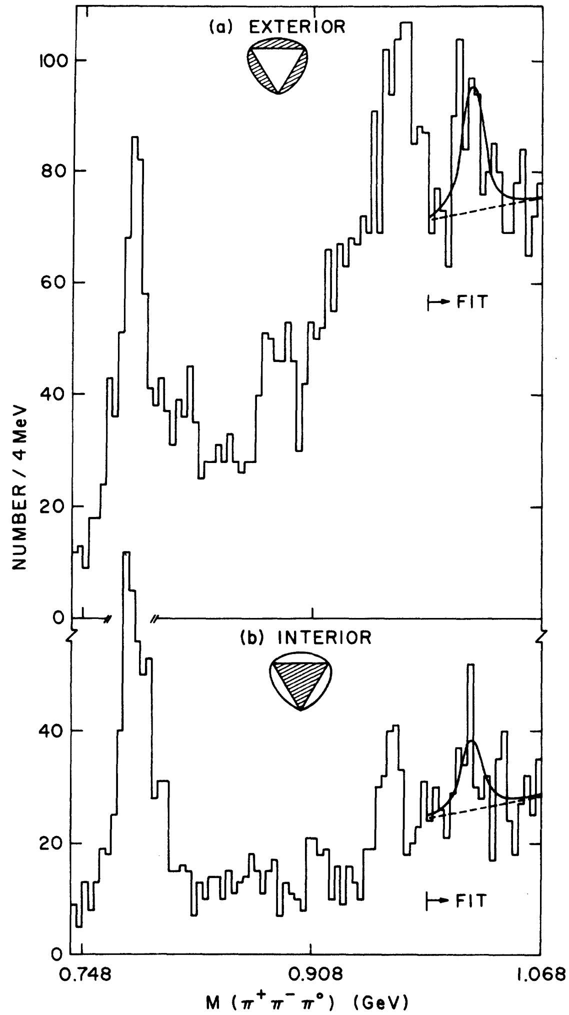

FIG. 2. Mass distribution of $\pi^+\pi^-\pi^0$ events separated into (a) exterior and (b) interior to "triangle" inscribed inside Dalitz area, as indicated by inset diagrams (see text). The solid fitted curves were used to determine the numbers of $\phi \to \pi^+\pi^-\pi^0$ in the exterior and interior regions (ϕ mass is constrained to its accepted value of 1019.7 MeV). The dashed curves are the estimated background levels.

A resolution-broadened ϕ signal plus linear background is fitted to the data above 0.988 GeV as in Fig. 1(c). The fitted curves are shown in Fig. 2, where the mass of the ϕ has been constrained to the accepted value of 1019.7 MeV. The numbers of $\phi \to 3\pi$ were determined to be 121 ± 35 and 67 ± 22 for the exterior and interior regions, respectively. In addition, the separate exterior regions corresponding to $\pi^+\pi^0$, $\pi^-\pi^0$, and $\pi^+\pi^-$ (not shown) were fitted similarly, yielding 55 ± 25, 70 ± 35, and 0 ± 30 $\phi \to 3\pi$ events, respectively. If $\phi \to 3\pi$ is described by phase space and angular momentum barriers essentially as in $\omega(783)$ decay, the ratio of events interior to events exterior should be 1.1 (as is the case for the ω data in Fig. 2). However, if $\phi \to 3\pi$ all proceeds via $\phi \to \rho\pi$, then a fraction 0.69 of the data should be exterior; that is, the ratio of events interior to exterior should be 0.45. The interior/exterior ratio is $(67 \pm 22)/(121 \pm 35) = 0.55 \pm 0.24$, consistent with 0.45 for all $\rho\pi$ final states and 2.3 standard deviations away from pure "phase space." Additionally, since the ϕ has isospin zero, the $\rho^+\pi^-$, $\rho^-\pi^+$, and $\rho^0\pi^0$ states should be equally populated. The three exterior regions are consistent with equal populations of $\frac{1}{3} \times 0.69 \times (195 \pm 62) = 45 \pm 14$ events as required by an $I = 0$ $\rho\pi$ state. Thus we conclude that the $\phi \to 3\pi$ decay appears to be dominated by $\rho(770)$ π final states, contrary to the expectation of Takasugi and Oneda.[7] Thus, either SU_2-breaking effects are important or another explanation for the discrepancy in the widths of ϕ and ψ, such as asymptotic freedom,[5,8] must be invoked.

In conclusion, we find $\phi \to K\bar{K}$ and 3π with properties consistent with other data. We find that the 3π decay appears to be dominated by $\rho\pi$ final states.

We acknowledge the support and encouragement of Professor B. Roe, Dr. N. P. Samios, and Dr. R. P. Shutt. We wish to thank Professor S. Oneda for his letter of inquiry about our $\phi \to 3\pi$ data which prompted this analysis.

*Work performed under the auspices of the Energy Research and Development Administration.

[1]Particle Data Group, Rev. Mod. Phys. 45, S1 (1973); Phys. Lett. 50B, 1 (1974).
[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).
[3]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).
[4]C. Bacci *et al.*, Phys. Rev. Lett. 33, 1408 (1974).
[5]A. De Rújula and S. L. Glashow, Phys. Rev. Lett. 34, 46 (1975).
[6]See, e.g., C. G. Callan *et al.*, Phys. Rev. Lett. 34, 52 (1975); J. Schwinger, *ibid.* 34, 37 (1975).
[7]E. Takasugi and S. Oneda, Phys. Rev. Lett. 34, 1129 (1975).
[8]A review on "asymptotic freedom" can be found in H. D. Politzer, Phys. Rep. 14C, 130 (1974).
[9]S. R. Borenstein *et al.*, Phys. Rev. D 5, 1559 (1972). The fitting procedure used is described therein. The width $\Gamma(\phi \to K^+K^-) = 3.8 \pm 0.5$ MeV is also given therein.
[10]S. R. Borenstein *et al.*, Phys. Rev. D 9, 3006 (1974). The discussion of different Breit-Wigner parameterizations is given therein.
[11]J.-E. Augustin *et al.*, Phys. Lett. 28B, 517 (1969).
[12]J. S. Lindsey and G. A. Smith, Phys. Rev. 147, 913 (1966); G. W. London *et al.*, *ibid.* 143, 1034 (1966).
[13]G. Cosme *et al.*, Phys. Lett. 48B, 155 (1974). (Their pure sample of 593 3π events could be analyzed for substructure $\rho^0\pi^0$ and $\rho^\pm\pi^\mp$).