the first interval could be in error, agreement could be obtained between theory and experiment for both knock-on and direct-pair interaction below 1 BeV of transferred energy.

The disagreement with knock-on theory is not unique to this experiment. As mentioned, the results of Gaebler *et al.*, when corrected for more recent energy estimates, show the same deviation. In addition, similar results have been found by Derry and Neddermeyer[6] for approximately the same region of energy transfer.

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Proton-Antiproton Annihilations into Two Mesons

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Proton-antiproton annihilation cross sections into two mesons are calculated assuming that contributions from the diagrams with a single intermediate meson dominate. Unitary symmetry and ω-ϕ mixing together with the total rates and cross sections for annihilation into two pseudoscalar mesons are used to obtain estimates of the derivative coupling constants for the ρ and Y mesons. (The Y meson is the member of the vector octet which is coupled to the hypercharge current.) The model is thus able to account for the annihilation into two pions and into two kaons, but yields results which are generally too large by an order of magnitude for the other two-meson final states of $p\bar{p}$ annihilations. It is pointed out that if the $\omega\rho\pi$ coupling constant, which is estimated from the 3π width of the ω, were smaller, and if the pseudoscalar meson intermediate states were neglected, then the model would yield a reasonably good description of the experiments.

I. INTRODUCTION

THE purpose of this paper is to discuss the consequences of a simple model for proton-antiproton annihilation into two mesons. The model assumes that the annihilation proceeds through a single intermediate vector meson or pseudoscalar meson state.

Berman and Oakes[1] have discussed nucleon-antinucleon annihilation from the point of view of a vector theory of strong interactions in which vector mesons are the dominant intermediate states. They have listed selection rules and several experimental consequences of these selection rules.

In this paper we will calculate explicitly cross sections and relative rates for proton-antiproton annihilations using both intermediate vector mesons and intermediate pseudoscalar mesons.

We will assume that the ρ meson is coupled universally to the isovector current.[2] From this assumption we obtain the ρNN vector coupling constant. The ρNN derivative coupling constant is obtained by fitting the the experimental $p\bar{p}$ annihilation cross section into two pions. Other coupling constants are obtained from considerations of unitary symmetry[3] and ω-ϕ mixing.[4,5] The results of the calculation for $K\bar{K}$ final states are, to a good approximation, independent of the amount of mixing as shown in Appendix B. We use experimental information at rest[6–8] and at 1.61 BeV/c.[9–12]

Our simple model for $p\bar{p}$ annihilations has been motivated by the following considerations. It has been observed[6] that the $p\bar{p}$ annihilations at rest occur predominantly from the S states of protonium. There are four distinct S states of protonium with quantum numbers J, I, G, C, P which exactly correspond to the

[1] S. M. Berman and R. J. Oakes, Nuovo Cimento **24**, 1329 (1963).
[2] J. J. Sakurai, Ann. Phys. (N. Y.) **11**, 1 (1960).
[3] M. Gell-Mann, California Institute of Technology Synchrotron Report, No. CTSL-20, 1961 (unpublished), and Phys. Rev. **125**, 1067 (1962); Y. Ne'eman, Nucl. Phys. **26**, 222 (1961).
[4] J. J. Sakurai, Phys. Rev. Letters **9**, 472 (1962).
[5] R. F. Dashen and D. H. Sharp, Phys. Rev. **133**, B1585 (1964).
[6] R. Armenteros, L. Montanet, D. R. O. Morrison, S. Nilsson, and A. Shapira, in *Proceedings of the International Conference on High-Energy Physics at CERN, 1962*, edited by J. Prentki (CERN, Geneva, 1962), pp. 351–356.
[7] N. Gelfand, D. Miller, M. Nussbaum, J. Rateau, J. Schultz *et al.*, Phys. Rev. Letters **11**, 438 (1963).
[8] N. Gelfand, D. Miller, M. Nussbaum, J. Rateau, J. Schultz *et al.*, Phys. Rev. Letters **11**, 436 (1963).
[9] G. R. Lynch, P. Eberhard, G. R. Kalbfleisch, J. E. Lannutti, B. C. Maglic *et al.*, Phys. Rev. **131**, 1287 (1963).
[10] N. Xuong and G. R. Lynch, Phys. Rev. **128**, 1849 (1962).
[11] B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson, Phys. Rev. Letters **7**, 178 (1961).
[12] G. R. Lynch, R. E. Faulks, G. R. Kalbfleisch, S. Limentani, J. B. Shafer *et al.*, Phys. Rev. **131**, 1276 (1963).

quantum numbers of the mesons π^0, η, ρ^0, ω (and/or ϕ). It is possible that these mesons are strongly coupled to the protonium S states, and we shall further assume that the single-meson states dominate at all energies.

The mesons are also coupled to each other and if we allow meson couplings of the form PPV and VVP where $P(V)$ is a pseudoscalar (vector) meson, then there are four basic diagrams for proton-antiproton annihilation into two mesons as shown in Fig. 1.

We note here the following simple consequence of our model. At all energies the intermediate states have the same quantum numbers as $p\bar{p}$ S states. Therefore there will be *no two-meson final states at any $\bar{p}$ energy which are not seen at rest* except possibly those for which the total rest energy is below threshold. For example, at any $\bar{p}$ energy, $p\bar{p}\to 2\pi^0$ is forbidden.

If we limit ourselves to π, η, K; ρ, ω, K^*, ϕ we may use Tables I and II of Berman and Oakes[1] to find the allowed intermediate and final states in $p\bar{p}\to$ one (virtual) meson $\to$ two mesons for PPV and PVV interactions. We list these in Table I.

In the following sections we will discuss the rates and cross sections for $p\bar{p}$ annihilations into the final states listed in Table I. We consider separately the cases PP, VV, and PV.

In Sec. II we find that for the case of 2π and $2K$ final states we are able to obtain results consistent with the experimental rates and cross sections although the angular distributions predicted by the model are not in complete agreement with the presently available data.

We find that a ratio of ρNN derivative coupling constant to ρNN vector coupling constant of -1.5 is necessary to explain the $p\bar{p}\to\pi^+\pi^-$ cross section. This may be compared to the value of 3.7 required to fit the isovector nucleon form factor at zero momentum transfer. It must be noted, however, that we are comparing the coupling constants for different values of momentum transfer.

For the case of $K\bar{K}$ annihilations we are able to obtain agreement with three independent pieces of experimental data (the total cross section at 1.61 BeV/c and two relative rates at rest) by introducing only one additional parameter—the derivative coupling constant for the interaction between nucleons and the Y meson. (The Y meson is the member of the vector-meson octet coupled to the hypercharge current.)

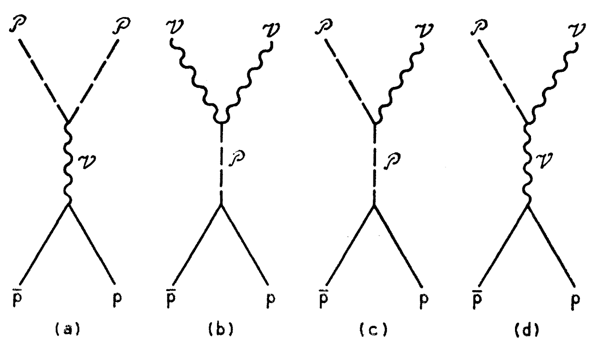

FIG. 1. Feynman diagrams for $p\bar{p}$ annihilation into two mesons through single-meson intermediate states. The solid lines represent nucleons (p or $\bar{p}$), the dashed lines represent pseudoscalar (P) mesons, and the wavy lines represent vector (V) mesons.

TABLE I. Allowed states in $p\bar{p}\to$ one (virtual) meson $\to$ two mesons. The intermediate states in parentheses require a VVV vertex which we do not allow.

	Allowed final states	Intermediate states
PP	$\pi^+\pi^-$	ρ^0
	K^+K^-	ρ^0, ω, ϕ
	$K^0\bar{K}^0$	ρ^0, ω, ϕ
VV	$2\rho^0$	η
	$\rho^+\rho^-$	η, (ρ^0)
	$\rho^0\omega$	π^0
	$K^{*0}\bar{K}^{*0}$	η, π^0, (ρ^0,ω,ϕ)
	$K^{*+}K^{*-}$	η, π^0, (ρ^0,ω,ϕ)
	$\rho^0\phi$	π^0
	2ω[a]	η
	2ϕ[a]	η
	$\omega\phi$[a]	η
PV	$\rho^0\pi^0$	ω, ϕ
	$\rho^0\eta$[a]	ρ^0
	$\rho^+\pi^-$	ω, ϕ, π^0
	$\rho^-\pi^+$	ω, ϕ, π^0
	$\omega\pi^0$	ρ^0
	$\phi\pi^0$	ρ^0
	$\omega\eta$	ω, ϕ
	$\phi\eta$	ω, ϕ
	$K^{*+}K^-$	π^0, η, ρ^0, ω, ϕ
	$K^{*-}K^+$	π^0, η, ρ^0, ω, ϕ
	$\bar{K}^{*0}K^0$	π^0, η, ρ^0, ω, ϕ
	$K^{*0}\bar{K}^0$	π^0, η, ρ^0, ω, ϕ

[a] These states were omitted from Tables I and II of Berman and Oakes (Ref. 1).

In Sec. III we discuss two vector-meson final states. Current experimental information places upper limits on the total cross sections. For those vector-meson pairs which occur only through a pion intermediate state, these upper limits are much smaller than the predictions of the model which are made using an $\omega\rho\pi$ coupling constant determined from the 3π width of the ω. For those vector-meson pairs which may occur only through an η intermediate state, these upper limits are consistent with a very weak coupling of η's to nucleons. For the vector-meson states which occur through both the π and η mesons, the pion contribution alone exceeds the upper limits established by experiment. Thus, if pion intermediate states are allowed, no value of the eta-nucleon coupling constant can be consistent with all the experimental results for two vector meson annihilations.

In Sec. IV we discuss final states which consist of a vector meson and a pseudoscalar meson. The model again predicts rates which are much larger than the upper limits established by experiment.

In Appendix A we list our conventions and effective interactions. In Appendix B we discuss ω-ϕ mixing and derive Eqs. (II.7) for $p\bar{p}\to K\bar{K}$.

II. ANNIHILATION INTO TWO PSEUDOSCALAR MESONS

A. Derivation of Cross Sections

We define an invariant amplitude $\mathfrak{M}$, in terms of which the differential cross section in the center-of-mass system averaged over initial and summed over final spins is given by

$$\frac{d\sigma}{d\Omega}=\frac{4\pi^2}{W^2}\frac{q}{p}\left[\tfrac{1}{4}\sum_{\text{all spins}}|\mathfrak{M}|^2\right], \tag{II.1}$$

where q is the magnitude of the three-momentum of an outgoing particle in the center-of-mass system, p is the magnitude of the three-momentum of the incoming $\bar{p}$ in the center-of-mass system, and $W=E_p+E_{\bar{p}}$ is the total center-of-mass energy.

In addition we shall express our results in terms of rationalized coupling constants defined, for example, by

$$\bar{g}_{\pi NN}^2=g_{\pi NN}^2/4\pi\cong 15\,,$$
$$\bar{f}_{\rho\pi\pi}^2=f_{\rho\pi\pi}^2/4\pi\cong 2\,.$$

In Appendix A we list the effective interaction Hamiltonians. In terms of these, we obtain in the center-of-mass system

$$\mathfrak{M}(\pi^+\pi^-)=\frac{i\bar{f}_{\rho\pi\pi}}{(4\pi)}\frac{W}{(Q_\mu Q_\mu+m_\rho^2)}\times\bar{v}_{\bar{p}}\left[\frac{\bar{f}_{\rho NN}}{2}A_\mu\gamma_\mu+\frac{\bar{g}_{\rho NN}}{4M_N}A_\nu\sigma_{\nu\beta}Q_\beta\right]u_p\,, \tag{II.2}$$

where $A_\mu\equiv q_\mu^+-q_\mu^-$ is the difference of the four-momenta of the π^+ and π^-, $\bar{p}_\mu$ is the four-momentum of the antiproton, p_μ is the four-momentum of the proton, u_p and $\bar{v}_{\bar{p}}$ are respectively the nucleon and antinucleon spinors, and $Q_\mu=p_\mu+\bar{p}_\mu=q_\mu^++q_\mu^-$ is the total four-momentum whose square is $Q_\mu Q_\mu=-W^2$. In obtaining Eq. (II.2) we have used the fact that $Q_\mu A_\mu=0$. Upon utilizing the Dirac equation and the fact that $Q_\mu A_\mu=0$, Eq. (II.2) can be transformed into

$$\mathfrak{M}(\pi^+\pi^-)=\frac{i\bar{f}_{\rho\pi\pi}}{2(4\pi)}\frac{W}{(-W^2+m_\rho^2)}\times\bar{v}_{\bar{p}}\left[(\bar{f}_{\rho NN}+\bar{g}_{\rho NN})A_\mu\gamma_\mu-\frac{i\bar{g}_{\rho NN}}{M_N}(A_\mu\bar{p}_\mu)\right]u_p\,. \tag{II.3}$$

If we now square $\mathfrak{M}(\pi^+\pi^-)$ and average over the initial spins, we obtain

$$\frac{d\sigma(\pi^+\pi^-)}{d\Omega}=\frac{\bar{f}_{\rho\pi\pi}^2}{8}\frac{q^3}{p(W^2-m_\rho^2)^2}\left[\bar{f}_{\rho NN}^2\left(\sin^2\theta+\frac{4M_N^2}{W^2}\cos^2\theta\right)+2\bar{f}_{\rho NN}\bar{g}_{\rho NN}+\bar{g}_{\rho NN}^2\left(\sin^2\theta+\frac{W^2}{4M_N^2}\cos^2\theta\right)\right], \tag{II.4}$$

where θ is the angle between the outgoing π^+ and the incoming proton, and q is the magnitude of the π^+ three-momentum. Integrating over angles we obtain the total cross section in the form

$$\sigma(\pi^+\pi^-)=\pi\frac{\bar{f}_{\rho\pi\pi}^2q^3}{3p(W^2-m_\rho^2)^2}\left[\bar{f}_{\rho NN}^2\left(1+\frac{2M_N^2}{W^2}\right)+3\bar{f}_{\rho NN}\bar{g}_{\rho NN}+\bar{g}_{\rho NN}^2\left(1+\frac{W^2}{8M_N^2}\right)\right]. \tag{II.5}$$

The amplitude for K^+K^- or $K^0\bar{K}^0$ annihilations may be obtained directly from the amplitude for $\pi^+\pi^-$ annihilations as follows. We note that there are three terms which contribute to the amplitude, corresponding to the three vector-meson intermediate states ρ^0, ω, and ϕ. We obtain the K-$\bar{K}$ annihilation amplitudes by the following substitutions:

$$\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{f}_{\rho NN}\rightarrow\pm\tfrac{1}{4}\bar{f}_{\rho KK}\bar{f}_{\rho NN}+\tfrac{3}{4}\bar{f}_{\omega KK}\bar{f}_{\omega NN}\left(\frac{W^2-m_\rho^2}{W^2-m_\omega^2}\right)+\tfrac{3}{4}\bar{f}_{\phi KK}\bar{f}_{\phi NN}\left(\frac{W^2-m_\rho^2}{W^2-m_\phi^2}\right), \tag{II.6a}$$

$$\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{g}_{\rho NN}\rightarrow\pm\tfrac{1}{4}\bar{f}_{\rho KK}\bar{g}_{\rho NN}+\tfrac{3}{4}\bar{f}_{\omega KK}\bar{g}_{\omega NN}\left(\frac{W^2-m_\rho^2}{W^2-m_\omega^2}\right)+\tfrac{3}{4}\bar{f}_{\phi KK}\bar{g}_{\phi NN}\left(\frac{W^2-m_\rho^2}{W^2-m_\phi^2}\right), \tag{II.6b}$$

where we take the $+$ sign for K^+K^- and the $-$ sign for $K^0\bar{K}^0$. The difference in sign occurs because the ρ meson is assumed coupled to an isovector $K\bar{K}$ current and the ω and ϕ mesons are assumed coupled to an isoscalar $K\bar{K}$ current.

Let us now assume[4,5] that the ω and ϕ mesons are mixtures of a Y meson coupled to the hypercharge current and a B meson coupled to the baryon current. We assume further that the Y meson is an octet partner of the ρ meson and that the vector octet is coupled universally to the F-spin current.[3] The "vector" type coupling constants of the vector octet are then determined from considerations of unitary symmetry and the $\rho\pi\pi$ coupling constant. We allow the "derivative" type couplings of the vector octet to be a mixture of F and D. The coupling constants of the ω and ϕ mesons are linear combinations of the coupling constants of the Y and B mesons as shown in Appendix B.

After substituting Eq. (II.6) into Eqs. (II.4) and (II.5) we can obtain a great simplification of the resulting expressions by neglecting the mass differences between the vector mesons. However, this approximation is not sufficiently accurate for our purposes. In order to obtain a better approximation we introduce a mass m which is intermediate between the mass of the

ϕ and the mass of the ω and which is defined by

$$m_\phi^2 = m^2 + \delta m^2\,,$$
$$m_\omega^2 = m^2 - \delta m^2\,.$$

We then expand the ω and ϕ propagators which appear in the amplitudes for $K\bar{K}$ production in powers of $\delta m^2/(W^2 - m^2)$, and retain only the lowest order terms.

It is now possible to cast the total cross sections in the following form:

$$\sigma(\pi^+\pi^-) = \sigma_0\left[\frac{2p^4}{M_N^2 W^2 x} + x\left(\alpha + \frac{3}{2x}\right)^2\right], \tag{II.7a}$$

$$\sigma(K^+K^-) = (q_K/q_\pi)^3\sigma_0\left[\frac{8p^4 z_1^2}{M_N^2 W^2 x} + \frac{1}{4}x\left(3u\beta + \alpha + \frac{6z_1}{x}\right)^2\right], \tag{II.7b}$$

$$\sigma(K^0\bar{K}^0) = (q_K/q_\pi)^3\sigma_0\left[\frac{2p^4 z_2^2}{M_N^2 W^2 x} + \frac{1}{4}x\left(3u\beta - \alpha + \frac{3z_2}{x}\right)^2\right], \tag{II.7c}$$

where

$$\sigma_0 = (\pi \bar{f}_{\rho\pi\pi}^4 q_\pi^3)/[3p(W^2 - m_\rho^2)^2]\,,$$
$$x = 1 + W^2/8M_N^2\,,$$
$$u = (W^2 - m_\rho^2)/(W^2 - m^2)\,,$$
$$z_1 = \tfrac{1}{4}(3u+1)\,,$$
$$z_2 = \tfrac{1}{2}(3u-1)\,,$$
$$\alpha = \bar{g}_{\rho NN}/\bar{f}_{\rho NN} = \bar{g}_{\rho NN}/\bar{f}_{\rho\pi\pi}\,,$$
$$\beta = \bar{g}_{YNN}/\bar{f}_{YNN} = \bar{g}_{YNN}/\bar{f}_{\rho\pi\pi}\,,$$

where q_π, q_K and p are the magnitudes of the three-momenta of the π, K, and proton in the center-of-mass frame where the total energy is W. We have taken $f_{\rho NN} = f_{\rho\pi\pi} = f_{YNN} = f_{YKK} = f_{\rho KK}$ in order to obtain Eq. (II.7).

B. Comparison with Experiment

Data on proton-antiproton annihilations into two pseudoscalar mesons have been obtained at rest[6] and at 1.61 BeV/c antiproton incident laboratory momentum.[9]

The relative rates at rest are given by[6]

$$R(\pi^+\pi^-) = (3.95 \pm 0.38)\times 10^{-3}\,,$$
$$R(K^+K^-) = (1.31 \pm 0.18)\times 10^{-3}\,,$$
$$R(K^0\bar{K}^0) = (0.56 \pm 0.08)\times 10^{-3}\,.$$

These rates are the number of such events divided by the total number of annihilations.

The cross sections[9] at 1.61 BeV/c are

$$\sigma(\pi^+\pi^-) = 119 \pm 30\ \mu\text{b}\,,$$
$$\sigma(K^+K^-) = 55 \pm 18\ \mu\text{b}\,.$$

Furthermore, at 1.61 BeV/c the angular distributions in the center-of-mass system indicate a forward peaking of the K^- and backward peaking of the π^- mesons. These cross sections are based upon 11 K^+K^- events and 22 $\pi^+\pi^-$ events.

We first consider the cross section $\sigma(\pi^+\pi^-)$ at 1.61 BeV/c incident antiproton laboratory momentum. The total cross section is given by Eq. (II.5). We first neglect derivative couplings (i.e., let $\bar{g}_{\rho NN} = 0$) and use the value $\bar{f}_{\rho\pi\pi}^2 = 2$ [obtained from $\rho \to 2\pi$ decay using $\Gamma(\rho \to 2\pi) = 100$ MeV], and take $\bar{f}_{\rho NN} = \bar{f}_{\rho\pi\pi}$ as dictated by the hypothesis that the ρ meson is coupled universally to the isovector current. We then obtain a cross section $\sigma(\pi^+\pi^-) = 225\ \mu$b, while the experimentally determined[9] cross section is $119 \pm 30\ \mu$b.

Neglecting derivative coupling also leads to a differential cross section which has an angular distribution which is symmetrical about $\theta = \pi/2$ and which is peaked slightly at $\theta = \pi/2$. This does not agree with the experimentally observed angular distribution which is depressed at $\theta = \pi/2$.

We obtain better agreement with experiment by introducing a nonzero derivative coupling constant. The total cross section may be fit with 2 values of $\bar{g}_{\rho NN}$: $\bar{g}_{\rho NN} = -0.24\bar{f}_{\rho NN} = -0.34$ or $\bar{g}_{\rho NN} = -1.5\bar{f}_{\rho NN} = -2.1$. The differential cross sections obtained using these values for $\bar{g}_{\rho NN}$ are shown in Fig. 2. Better agreement with the experimental data is obtained for $\bar{g}_{\rho NN} = -2.1$.

However, we note that all the theoretical curves have forward-backward symmetry, while this is not so for the experimental data. In view of the fact that only 22 $\pi^+\pi^-$ events were contained in the experimental sample, we feel that firm conclusions concerning the angular distribution should await further data.

We next consider the K^+K^- annihilation cross section. From Table I we see that there are 3 intermediate states possible: ρ^0, ω, and ϕ. Let us first assume that only the ρ^0 state is important as in the $\pi^+\pi^-$ case. Then assuming

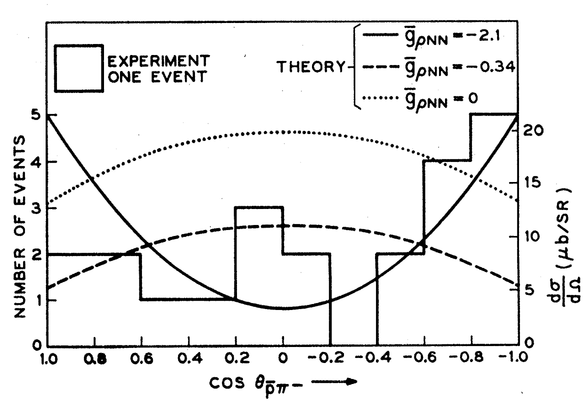

FIG. 2. Differential cross sections in the center-of-mass system for $p\bar{p} \to \pi^+\pi^-$ at 1.61 BeV/c. The theoretical curves are obtained for three different values of the derivative coupling constant of the ρ meson to nucleons. The experimental data are taken from Ref. 9.

universal ρ meson coupling we immediately have

$$\sigma(K^+K^-)/\sigma(\pi^+\pi^-)=\tfrac{1}{4}(q_K/q_\pi)^3=0.19$$

at 1.61 BeV/c $\bar{p}$ laboratory momentum, while experimentally[9] $\sigma(K^+K^-)/\sigma(\pi^+\pi^-)\approx 0.46\pm 0.20$. In addition, the rate of K^+K^- production would be the same as the rate of $K^0\bar{K}^0$ production if only the ρ meson were important, whereas experimentally, at rest,[6] the number of charged K pairs are greater by a factor of 2. Thus, we are led to the necessity of including the ω and ϕ meson intermediate states.

We now make use of our former assumption[4,5] that the ω and ϕ mesons are mixtures of a Y meson coupled to the hypercharge current and a B meson coupled to the baryon current. Since the Y and ρ meson belong to the same octet we have $\bar{f}_{YNN}=\bar{f}_{YKK}=\bar{f}_{\rho NN}$. Choosing $\alpha=\bar{g}_{\rho NN}/\bar{f}_{\rho NN}=-1.5$, as obtained by fitting the $\pi^+\pi^-$ cross section, the rates and cross sections for $K\bar{K}$ production are determined from Eqs. (II.7b)–(II.7c) by the value of just one parameter—namely $\beta=\bar{g}_{YNN}/\bar{f}_{YNN}$.

We shall take the point of view that this parameter is to be determined from experimental data. We use the total cross sections at 1.61 BeV/c and the relative rates at rest to determine three pairs of solutions for β. These are listed in Table II. We see that $\beta\approx -1.0$ gives a good fit to all the data.

We have also calculated the differential cross section $d\sigma(K^+K^-)/d\Omega$ at 1.61 BeV/c. The angular distribution is peaked strongly in the forward and backward directions. Experimentally[9] 7 of the 11 observed K^- are in the forward ($\bar{p}$) direction. Since there were only 11 events we prefer not to make any firm statements concerning the angular distributions, but rather await further data.

Finally, we have calculated the three pairs of values for β obtained by using $\alpha=-0.24$. Our results are given in Table II. It is interesting to note that we obtain a good fit to all the total cross sections and relative rates with $\beta\approx -0.9$, not very different from our previous value. However, in this case the angular distribution of the K^- mesons is depressed in the forward and backward directions in complete contradiction to the experimental results. This further supports the choice of $\alpha=-1.5$.

We conclude this section by noting that our model for proton-antiproton annihilation into $\pi^+\pi^-$ and $K\bar{K}$ through a single intermediate vector meson yields agreement with most of the available experimental data.

TABLE II. Values of $\beta=\bar{g}_{YNN}/\bar{f}_{YNN}$ determined from experiment.

Fitted quantity	$\alpha=-1.5$ β		$\alpha=-0.24$ β	
$\sigma(K^+K^-)$ at 1.61 BeV/c $=55\pm 18$ μb	-0.90	-0.43	-0.82	-1.29
Rate (K^+K^-)/rate $(K^0\bar{K}^0)$ at rest$=2.34\pm 0.76$	-1.03	-1.70	-0.95	$+0.10$
Rate $(\pi^+\pi^-)$/rate (K^+K^-) at rest$=3.02\pm 0.41$	-1.07	-0.64	-0.90	-1.57

III. ANNIHILATION INTO TWO VECTOR MESONS

In this section we shall obtain formulas for anihilation into two vector mesons.

Consider first those final states where only a π^0 intermediate state is possible. These are $\rho^0\omega$ or $\rho^0\phi$. Using the interaction given in Appendix A, we have

$$\mathfrak{M}(\rho^0\omega)=\bar{f}_{\omega\rho\pi}\bar{g}_{\pi NN}\frac{W\epsilon_{\alpha\beta\gamma\delta}}{4\pi}\frac{k_\alpha{}^\omega e_\beta{}^\omega k_\gamma{}^\rho e_\delta{}^\rho}{(-W^2+m_\pi{}^2)}(\bar{v}_{\bar{p}}\gamma_5 u_p)\,,\quad\text{(III.1)}$$

where $\epsilon_{\alpha\beta\gamma\delta}$ is the completely antisymmetric tensor with $\epsilon_{1234}=1$, k^ω, $e^\omega(k^\rho,e^\rho)$ are the momenta and polarization vectors of the outgoing $\omega(\rho)$, and W is once again the total center-of-mass energy.

Summing over the ω, ρ polarizations and averaging over nucleon spins, we obtain the isotropic cross section in the center-of-mass system

$$\sigma(\rho^0\omega)=4\pi\frac{d\sigma}{d\Omega}(\rho^0\omega)=\pi\bar{f}_{\omega\rho\pi}{}^2\bar{g}_{\pi NN}{}^2\frac{q^3W^2}{p(W^2-m_\pi{}^2)^2}\,,\quad\text{(III.2)}$$

where q is the magnitude of the ρ^0 three-momentum and p is the magnitude of the $\bar{p}$ three-momentum in the center-of-mass system.

If we take $\bar{g}_{\pi NN}{}^2=15$ and use a value of $\bar{f}_{\omega\rho\pi}{}^2\approx 0.4/m_\pi{}^2$ which is obtained[5] from the assumption that the $\omega\to 3\pi$ decay proceeds via $\omega\to\pi+\rho\to 3\pi$, then we find from Eq. (III.2), $\sigma(\rho^0\omega)\approx 68$ mb at 1.61 BeV/c, whereas experimentally the total $2\pi^++2\pi^-+\pi^0$ cross section is[10] ≈ 10 mb and the mass spectra are consistent with no $\rho^0\omega$ pairs.[11] Although it is impossible to distinguish a $\rho^0\omega$ state from a state containing an ω and 2π in which the two-pion effective mass happens to be in the ρ-mass region, it is clear that the chosen values of the coupling constants lead to contradiction with experiment.

In exactly the same manner as Eq. (III.2) was obtained, we can obtain

$$\sigma(\rho^0\phi)=\pi\bar{g}_{\pi NN}{}^2\bar{f}_{\phi\rho\pi}{}^2\frac{q^3W^2}{p(W^2-m_\pi{}^2)^2}\,.\quad\text{(III.3)}$$

If we compute $\bar{f}_{\phi\rho\pi}$ from $\bar{f}_{\omega\rho\pi}$ using the ω-ϕ mixing model[5] and the assumption that $\bar{f}_{B\rho\pi}(\equiv\bar{f}_1)=0$, we obtain from Eq. (III.3) $\sigma(\rho^0\phi)\approx 80$ mb. The experimental limit[10] for $K\bar{K}\pi\pi$ events at 1.61 BeV/c is ≈ 2 mb.

For $p\bar{p}$ annihilations at rest, a sample[7] of $K^+K^-\pi^+\pi^-$ events in which both the K^+ and K^- stopped in the bubble chamber shows no evidence of ρ^0's produced with the observed ϕ's.

Let us now consider processes where the η is the only possible intermediate state. (See Table I.) In order to obtain formulas for the cross sections, we will again make use of ω-ϕ mixing and SU_3. Let f_8 and f_1 denote the coupling constants of the octet and singlet vector mesons[13] to $\boldsymbol{\rho}\cdot\boldsymbol{\pi}$. Then in terms of the mixing parameters

[13] See Eqs. (A2) and (A3) of this Appendix. There, the identification of ω with the octet and ϕ with the singlet is made.

a and b we find

$$\bar{f}_{\omega\rho\pi}=a\bar{f}_1-b\bar{f}_8\,,\quad \bar{f}_{\phi\rho\pi}=b\bar{f}_1+a\bar{f}_8\,. \tag{III.4}$$

For η intermediate states and two-vector meson final states, we can obtain the cross sections from Eq. (III.2) by replacing m_π^2 by m_η^2, q by the appropriate final three-momentum, and $\bar{g}_{\pi NN}$ by $\bar{g}_{\eta NN}$. Let

$$R=\frac{\pi}{p}\bar{g}_{\eta NN}^2\frac{W^2}{(W^2-m_\eta^2)^2}\,, \tag{III.5}$$

then

$$\sigma(2\rho^0)=R\bar{f}_8^2q_\rho^3\,, \tag{III.6}$$

$$\sigma(\rho^+\rho^-)=R\bar{f}_8^2q_\rho^3\,, \tag{III.7}$$

$$\sigma(2\omega^0)=R(-b^2\bar{f}_8-2ab\bar{f}_1)^2q_\omega^3\,, \tag{III.8}$$

$$\sigma(2\phi)=R(-a^2\bar{f}_8+2ab\bar{f}_1)^2q_\phi^3\,, \tag{III.9}$$

$$\sigma(\omega\phi)=R(ab\bar{f}_8+(a^2-b^2)\bar{f}_1)^2q_\omega^3\,, \tag{III.10}$$

where q_ρ, q_ω, q_ϕ are the magnitudes of the three-momenta of the outgoing particles.

Proton-antiproton annihilations into $K^*\bar{K}^*$ may proceed through both η and π meson intermediate states. The total cross sections are given by

$$\sigma(K^{*+}K^{*-})=\frac{\pi}{p}\bar{f}_8^2\left(\frac{\sqrt{3}}{2}\frac{\bar{g}_{\pi NN}}{W^2-m_\pi^2}-\frac{1}{2}\frac{\bar{g}_{\eta NN}}{W^2-m_\eta^2}\right)^2W^2q_{K^*}^3\,, \tag{III.11}$$

$$\sigma(\bar{K}^{*0}K^{*0})=\frac{\pi}{p}\bar{f}_8^2\left(\frac{\sqrt{3}}{2}\frac{\bar{g}_{\pi NN}}{W^2-m_\pi^2}+\frac{1}{2}\frac{\bar{g}_{\eta NN}}{W^2-m_\eta^2}\right)^2W^2q_{K^*}^3\,. \tag{III.12}$$

The cross sections (III.6) to (III.10) are extremely sensitive to the F/D ratio in the coupling of pseudoscalar mesons to baryons which determine $\bar{g}_{\eta NN}^2$ assuming $\bar{g}_{\pi NN}^2=15$. Recent calculations[14] indicate that the F/D ratio is such that a value of $\bar{g}_{\eta NN}\approx 0$ is reasonable.

In a sample[8] of $\pi^+\pi^-\pi^0K^+K^-$ events where the K^+ and K^- both stopped in the bubble chamber, the effective mass of those K^+K^- which are paired with an ω shows little evidence of a ϕ. In other words, there is no experimental evidence for $\phi\omega$ pairs produced in $p\bar{p}$ annihilations at rest. This is consistent with a small value of $\bar{g}_{\eta NN}$.

We can again use the ω-ϕ mixing model[5] together with the estimates of $f_{\omega\rho\pi}$ and $f_{\phi\rho\pi}$ to obtain an estimate of f_8. Assuming that $\bar{g}_{\eta NN}$ is negligible compared to $\bar{g}_{\pi NN}$, we then find a total $K^*\bar{K}^*$ cross section at 1.61 BeV/c of over 150 mb whereas experiment[10] indicates $\sigma(p\bar{p}\to KK\pi\pi)\approx 2$ mb.

Certainly more experimental information on the cross sections for annihilation into two vector mesons is desirable. It is to be noted that at present there are no observations of two-vector meson annihilations. Within the framework of the model we may explain this by asserting that the value of $f_{\omega\rho\pi}$ obtained from the width of the ω is too large by at least an order of magnitude. It would be of interest to obtain another independent estimate of the $\omega\rho\pi$ coupling constant.

Alternatively, one may take the point of view of Berman and Oakes[1] that only intermediate vector-meson states occur. Then, since there are no pseudoscalar meson intermediate states, annihilations into two vector mesons are strictly forbidden. This approach would also yield agreement with the present experimental data.

IV. ANNIHILATION INTO A VECTOR MESON AND A PSEUDOSCALAR MESON

There are two types of diagrams for $p\bar{p}$ annihilation into a vector meson and a pseudoscalar meson. These are shown in Figs. 1(c) and 1(d).

We consider first the annihilation reactions $p\bar{p}\to\rho^-\pi^+(\rho^+\pi^-)$. The possible intermediate states for these reactions are π^0, ω, and ϕ. Once again we assume that the ω and ϕ mesons are mixtures of a B meson coupled to the baryon current and a Y meson coupled to the hypercharge current. In order to make numerical estimates we shall neglect the $B\rho\pi$ coupling. We obtain the matrix element for $\rho^-\pi^+(\rho^-\pi^+)$ as

$$\mathfrak{M}(\rho^-\pi^+)=\frac{W}{4\pi}\bar{v}_{\bar{p}}\left\{\frac{\bar{g}_{\pi NN}[-\bar{f}_{\rho\pi\pi}e_\alpha{}^\rho(Q_\alpha+K_\alpha{}^\pi)]\gamma_5}{Q_\mu Q_\mu+m_\pi^2}+\frac{\sqrt{3}}{2}\frac{\bar{f}_{Y\rho\pi}[\bar{f}_{YNN}\gamma_\mu A_\mu+(\bar{g}_{YNN}/2M_N)A_\mu\sigma_{\mu\nu}Q_\nu]}{Q_\mu Q_\mu+m^2}\right\}u_p\,, \tag{IV.1}$$

where $m^2=\frac{1}{2}(m_\omega^2+m_\phi^2)$ and we have neglected terms of order $(m_\phi^2-m_\omega^2)/(W^2-m^2)$.

In Eq. (IV.1) $A_\mu=i\epsilon_{\alpha\mu\gamma\delta}Q_\alpha K_\gamma{}^\rho e_\delta{}^\rho$, e^ρ is the polarization of the ρ, $K^\rho(K^\pi)$ is the four-momentum of the $\rho(\pi)$ and Q_μ is the total four-momentum, so that $Q_\mu Q_\mu=-W^2$. All quantities refer to the over-all center-of-mass frame.

Upon averaging over nucleon spins and summing over ρ polarizations, we find

$$\frac{d\sigma(\rho^-\pi^+)}{d\Omega}=\frac{W^2q^3}{4p}\left\{\frac{2\bar{f}_{\rho\pi\pi}^2\bar{g}_{\pi NN}^2}{m_\rho^2(W^2-m_\pi^2)^2}+\frac{3}{4}\frac{\bar{f}_{Y\rho\pi}^2}{(W^2-m^2)^2}\times\left[(\bar{f}_{YNN}+g_{YNN})^2+\left(\frac{W^2-4M_N^2}{2W^2}\right)\times\left(\frac{W^2}{4M_N^2}\bar{g}_{YNN}^2-\bar{f}_{YNN}^2\right)\sin^2\theta_{\bar{p}\rho^-}\right]\right\}\,. \tag{IV.2}$$

Note that there are no interference terms between the Y and π intermediate states; these terms vanish upon averaging over initial spins. Integrating Eq. (IV.2)

[14] Yasuo Hara, Phys. Rev. **133**, B1565 (1964); see Hara's Eq. (3.6); A. W. Martin and K. C. Wali, Phys. Rev. **130**, 2455 (1963); and Nuovo Cimento **31**, 1324 (1964).

over angles we obtain

$$\sigma(\rho^-\pi^+)=\frac{\pi W^2 q^3}{p}\left\{\frac{2\bar{f}_{\rho\pi\pi}{}^2\bar{g}_{\pi NN}{}^2}{m_\rho{}^2(W^2-m_\pi{}^2)^2}+\frac{3}{4}\frac{\bar{f}_{Y\rho\pi}{}^2}{(W^2-m^2)^2}\right.$$
$$\times\left[(\bar{f}_{YNN}+\bar{g}_{YNN})^2+\frac{1}{3}\left(\frac{W^2-4M_N{}^2}{W^2}\right)\right.$$
$$\left.\left.\times\left(\frac{W^2}{4M_N{}^2}\bar{g}_{YNN}{}^2-\bar{f}_{YNN}{}^2\right)\right]\right\}. \quad \text{(IV.3)}$$

The term involving the intermediate π yields a contribution of 40 mb at 1.61 BeV/c incident $\bar{p}$ lab momentum while the total experimental[12] $\pi^+\pi^-\pi^0$ cross section is 1.6 mb and very few $\rho\pi$ pairs are observed.[15]

Since the contribution to the cross section from the intermediate pion state is so large, let us consider the modification of the model suggested in Sec. III. We neglect the pion contribution and consider only the contribution from the vector mesons.

The vector meson contribution to the rate at rest is proportional to $(\bar{g}_{YNN}+\bar{f}_{YNN})^2$. In Sec. II we found that we obtained a good fit to the $p\bar{p}\rightarrow K\bar{K}$ data by choosing $\bar{g}_{YNN}=-\bar{f}_{YNN}$. However, this yields a vanishing rate for the reaction $p\bar{p}\rightarrow\rho\pi$ at rest. Thus for annihilations at rest we must consider the next order term in $(m_\phi{}^2-m_\omega{}^2)/(W^2-m^2)$. This term contains contributions from the B meson with unknown coupling constants. It would therefore be of interest to obtain the absolute rate for $p\bar{p}\rightarrow\rho\pi$ at rest.

The vector-meson term also yields cross sections and rates which are equal for all three $\rho\pi$ charge states. This agrees with the data for annihilation at rest.[15] (If we include the intermediate pion state then the charged modes are enhanced.)

At 1.61 BeV/c the lowest order term in the cross section is nonvanishing for $\beta=\bar{g}_{YNN}/\bar{f}_{YNN}=-1$. This yields the result $\sigma(p\bar{p}\rightarrow\rho^-\pi^+)\approx 2$ mb. Hence, for all charge states $(p\bar{p}\rightarrow\rho\pi)\approx 6$ mb. Experimentally[12] at 1.61 BeV/c the total cross section for 3π annihilations is ≈ 1.6 mb, and from the mass distributions it is clear that the $\rho\pi$ cross section must be at least an order of magnitude smaller.

Thus, we see that even neglecting the contribution from the intermediate pion state, the theoretical result exceeds the experimental upper limit by almost two orders of magnitude. We note, as in Sec. III, that this result is dependent upon the value for $f_{\omega\rho\pi}$ obtained from the $\omega\rightarrow 3\pi$ width. We clearly obtain better agreement with the data if $f_{\omega\rho\pi}$ is reduced by an order of magnitude.

The state $\rho^0\eta$ arises through only a ρ^0 meson intermediate state. Consequently only the vector term contributes. Using SU_3 invariance to determine $f_{\rho\rho\eta}$ and our previous result that $\bar{g}_{\rho NN}=-1.5\bar{f}_{\rho NN}$ we obtain $\sigma(\rho^0\eta)\approx 1$ mb at 1.61 BeV/c. The data[11] indicate no evidence for $\rho^0\eta$ pairs in $p\bar{p}$ annihilations.

Similarly we obtain $\sigma(\phi\pi^0)\approx 3$ mb at 1.61 BeV/c. At this energy the total cross section for $K\bar{K}\pi$ final states is ≈ 0.7 mb.[10] It would be of interest to determine the fraction of ϕ's in the $K\bar{K}$ distributions in order to make a better comparison with the theoretical estimates.

The $\omega\pi^0$ final state which also proceeds through only an intermediate ρ^0 meson is unobservable.

The final states $\phi\eta$ and $\omega\eta$ proceed through ω and ϕ meson intermediate states. The cross sections may be obtained using the ω-ϕ mixing model. We note that the state $\omega\eta$ is unobservable and the $\phi\eta$ state has not been observed at rest.

Finally, we note that the annihilation into $K^*\bar{K}(\bar{K}^*K)$ final states proceeds through *all* the intermediate meson states. We obtain separate contributions from the pseudoscalar and vector-meson intermediate states. However, each contribution exceeds the experimental upper limit for $p\bar{p}\rightarrow K\bar{K}\pi$ of less than 1 mb at 1.61 BeV/c.[10]

Thus all the theoretical predictions for annihilations into a pseudoscalar and vector meson which may be compared with experimental data exceed the experimental limits. In all cases we obtain much better agreement with the data if $f_{\omega\rho\pi}$ is reduced by an order of magnitude.

V. SUMMARY

In this paper we have considered $p\bar{p}$ annihilations into two-meson final states. We have attempted to explain the available experimental data in terms of a model which assumes that the annihilation proceeds through a single-meson intermediate state.

We have made use of SU_3 symmetry and ω-ϕ mixing to construct the interactions and we have assumed that the vector octet is coupled universally to the F-spin current.

For annihilation into two pseudoscalar mesons we have found that we are able to fit four independent pieces of experimental data using two parameters, i.e., the derivative coupling constants of the ρ and Y mesons. These data are the cross sections $\sigma(\pi^+\pi^-)$ and $\sigma(K^+K^-)$ at 1.61 BeV/c and the relative rates $R(\pi^+\pi^-):R(K^+K^-):R(K^0\bar{K}^0)$ at rest. Our results are $g_{\rho NN}=-1.5f_{\rho NN}$ and $g_{YNN}=-f_{YNN}$.

In addition, our model predicts angular distributions for the final states $\pi^+\pi^-$ and K^+K^-. We obtain reasonable agreement with the pion angular distribution, but a poor fit with the kaon angular distribution. We note that there are only 11 events in the K^+K^- experimental sample. It would be of great interest to obtain more data on annihilation into K^+K^- since the angular distribution provides a critical test of the model.

We have calculated cross sections for $p\bar{p}$ annihilation into two vector mesons and found that our predictions

[15] Annihilations at rest do seem to produce many $\rho\pi$ pairs in the 3π mode. See G. B. Chadwick, W. T. Davies, M. Derrick, G. J. B. Hawkins, J. H. Mulvey *et al.*, Phys. Rev. Letters **10**, 62 (1963).

are in general larger in magnitude than the upper limits permitted by the currently available experimental data. The theory may be brought into much better agreement with the experimental data by either (a) neglecting the pseudoscalar meson intermediate states (this yields a vanishing result for all two vector-meson final states which is not inconsistent with the data); or (b) reducing the value of the VVP coupling constants obtained from $f_{\omega\rho\pi}$. It should be pointed out that $f_{\omega\rho\pi}$ is determined from the 3π width of the ω assuming that the ω decays via the two-step process $\omega \to \rho+\pi \to 3\pi$. We may take the point of view that our calculations may be used to determine $f_{\omega\rho\pi}$. In this case we estimate that its value should be reduced by an order of magnitude from the currently accepted value.[5]

Our calculations of the cross sections for annihilation into a final state containing a pseudoscalar meson and a vector meson contain separate contributions from the pseudoscalar and vector meson intermediate states. Both terms exceed the experimental upper limits so that we can obtain agreement with the data only by *both* (a) neglecting the pseudoscalar meson intermediate states and (b) reducing the value of $f_{\omega\rho\pi}$. We note that assumption (a) is a return to the original model of Berman and Oakes.[1]

It should be pointed out that the model makes definite predictions for the rates and cross sections for $p\bar{p} \to \phi\pi^0$ and $p\bar{p} \to K^*\bar{K}$. However, we are not aware of any experiment which analyzes the data for $p\bar{p} \to K\bar{K}\pi$ in this way. It would be of interest to obtain an analysis of the data in terms of these reactions.

Finally, we note that the modified model incorporating a lower value for $f_{\omega\rho\pi}$ is able to give reasonable agreement with all the presently available experimental data for proton-antiproton annihilations into two mesons.

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APPENDIX A: CONVENTIONS AND EFFECTIVE INTERACTIONS

(a) Conventions

We take $\hbar=c=1$. The Lorentz indices run from 1–4 and $x_4=it=ix_0$. We use four Hermitian γ matrices which satisfy $\gamma_\mu\gamma_\nu+\gamma_\nu\gamma_\mu=2\delta_{\mu\nu}$, $\gamma_5=\gamma_1\gamma_2\gamma_3\gamma_4$, and $\sigma_{\mu\nu}\equiv(1/2i)(\gamma_\mu\gamma_\nu-\gamma_\nu\gamma_\mu)$. The nucleon spinors are normalized by $u_p{}^\dagger u_p=1$ and antinucleon spinors likewise by $v_{\bar{p}}{}^\dagger v_{\bar{p}}=1$, and $\bar{v}_{\bar{p}}=v_{\bar{p}}{}^\dagger\gamma_4$. Averaging over spins is accomplished by means of

$$\sum_{\text{spins}} u_p\bar{u}_p=(M_N-i\gamma_\mu p_\mu)/(2|E_p|)$$

and

$$\sum_{\text{spins}} v_{\bar{p}}\bar{v}_{\bar{p}}=(-M_N-i\gamma_\mu p_\mu)/(2|E_{\bar{p}}|).$$

(b) Effective Interactions

Let π^+, ρ^+, K^+, etc., denote the field operators which destroy the corresponding particles. Let K be a column vector of (K^+,K^0) and $K_\mu{}^*$ likewise a column vector of $(K_\mu{}^{*+}, K_\mu{}^{*0})$. Denote by $\bar{K}$ the Hermitian conjugate row vector $(K^-,\bar{K}^0)$ and denote by $\bar{K}_\mu{}^*$ the row vector $(K_\mu{}^{*-},K_\mu{}^{*0})$. (Note that $K_i{}^{*-}$ is the Hermitian conjugate of $K_i{}^{*+}$ for $i=1$, 2, 3 and $K_4{}^{*-}$ is minus the Hermitian conjugate of $K_4{}^{*+}$.)

$$\begin{aligned}H(VPP)=&\tfrac{1}{2}f_{\rho\pi\pi}\boldsymbol{\rho}_\alpha\cdot(\partial_\alpha\boldsymbol{\pi}\times\boldsymbol{\pi}-\boldsymbol{\pi}\times\partial_\alpha\boldsymbol{\pi})+\tfrac{1}{2}if_{\rho KK}[(\partial_\alpha\bar{K})\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\alpha K-\bar{K}\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\alpha\partial_\alpha K]\\&+\tfrac{1}{2}if_{\pi KK^*}\{[\bar{K}\boldsymbol{\tau}\cdot\partial_\alpha\boldsymbol{\pi}-(\partial_\alpha\bar{K})\boldsymbol{\tau}\cdot\boldsymbol{\pi}]K_\alpha{}^*-\bar{K}_\alpha{}^*[(\boldsymbol{\tau}\cdot\partial_\alpha\boldsymbol{\pi})K-\boldsymbol{\tau}\cdot\boldsymbol{\pi}\partial_\alpha K]\}+i(\sqrt{3}/2)[f_{\omega KK}\omega_\alpha+f_{\phi KK}\phi_\alpha]\\&\times[(\partial_\alpha\bar{K})K-\bar{K}\partial_\alpha K]+i(\sqrt{3}/2)f_{\eta KK^*}\{[\bar{K}\partial_\alpha\eta-(\partial_\alpha\bar{K})\eta]K_\alpha{}^*-\bar{K}_\alpha{}^*[(\partial_\alpha\eta)K-\eta\partial_\alpha K]\}.\end{aligned}\tag{A1}$$

For the VVP interaction we use the coupling $\epsilon_{\alpha\beta\gamma\delta}(\partial_\alpha V_\beta)(\partial_\gamma V_\delta)P$. Omitting, for brevity, the Lorentz indices and assuming that ω is pure octet and that ϕ is pure singlet, we take

$$\begin{aligned}H(V_8V_8P)=&if_{\omega\rho\pi}\omega\boldsymbol{\pi}\cdot\boldsymbol{\rho}+(\tfrac{1}{2}i)f_{\eta\rho\rho}\eta\boldsymbol{\rho}\cdot\boldsymbol{\rho}-(\tfrac{1}{2}i)f_{\omega\omega\eta}\omega\omega\eta+i(\sqrt{3}/2)f_{K^*\rho K}[\bar{K}\boldsymbol{\tau}\cdot\boldsymbol{\rho}K^*+\bar{K}^*\boldsymbol{\tau}\cdot\boldsymbol{\rho}K]\\&+i(\sqrt{3}/2)f_{K^*K^*\pi}\bar{K}^*\boldsymbol{\tau}\cdot\boldsymbol{\pi}K^*-\tfrac{1}{2}if_{\eta K^*K^*}\eta\bar{K}^*K^*+(\tfrac{1}{2}i)f_{\omega K^*K}[\omega\bar{K}^*K+\omega\bar{K}K^*],\end{aligned}\tag{A2}$$

$$H(V_1V_8P)=i\phi[f_{\phi\rho\pi}\boldsymbol{\rho}\cdot\boldsymbol{\pi}+f_{\phi\omega\eta}\omega\eta+f_{\phi K^*K}(\bar{K}^*K+\bar{K}K^*)].\tag{A3}$$

In the limit of pure SU_3, with ω a member of an octet, and ϕ a singlet all of the coupling constants in Eq. (A1) (except for $f_{\phi KK}$) would be equal to $f_{\rho\pi\pi}$. Similarly, in Eq. (A2) all of the f's would be equal to each other and again all of the f's in Eq. (A3) would be equal to each other.

For the couplings to nucleons we take

$$\begin{aligned}H(N)=&-ig_{\pi NN}\bar{N}\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N-ig_{\eta NN}\bar{N}\gamma_5N\eta-i\bar{N}\tfrac{1}{2}\boldsymbol{\tau}\cdot\left[f_{\rho NN}\gamma_\mu\boldsymbol{\rho}_\mu+\frac{ig_{\rho NN}}{2M_N}\sigma_{\mu\nu}(\partial_\nu\boldsymbol{\rho}_\mu)\right]N\\&-i\bar{N}(\sqrt{3}/2)\left[f_{\omega NN}\gamma_\mu\omega_\mu+\frac{ig_{\omega NN}}{2M_N}\sigma_{\mu\nu}(\partial_\nu\omega_\mu)\right]N-i\bar{N}(\sqrt{3}/2)\left[f_{\phi NN}\gamma_\mu\phi_\mu+\frac{ig_{\omega NN}}{2M_N}\sigma_{\mu\nu}(\partial_\nu\phi_\mu)\right]N.\end{aligned}\tag{A4}$$

The factors of $\sqrt{3}/2$ are included so that for exact SU_3 invariance, if ρ and ω are octet partners coupled to the F spin we would have $f_{\rho NN}=f_{\omega NN}$. We have written our Hamiltonians in terms of unrationalized coupling constants and we take $g_{\pi NN}^2/4\pi\approx 15$.

APPENDIX B: ω-ϕ MIXING AND $p\bar{p}\to K\bar{K}$

In this Appendix we shall derive Eqs. (II.7b) and (II.7c) and show that to a good approximation, the rates of proton-antiproton annihilations into $K\bar{K}$ are independent of the amount of ω-ϕ mixing.

We assume that the ω and ϕ are mixtures of a Y meson coupled to the hypercharge current and a B meson coupled to the baryon current. The Y meson is assumed to be an octet partner of the ρ meson which is coupled universally to the isospin current. We have for the meson fields

$$\omega_\mu=aB_\mu-bY_\mu\,,\quad \phi_\mu=bB_\mu+aY_\mu \tag{B1}$$

and the inverse equations

$$Y_\mu=a\phi_\mu-b\omega_\mu\,,\quad B_\mu=a\omega_\mu+b\phi_\mu\,, \tag{B2}$$

where $a^2+b^2=1$.

The hypercharge current $J_\mu{}^{(Y)}$ and the baryon current $J_\mu{}^{(B)}$ contain the isoscalar nucleon current $J_\mu{}^{(N)}$ and the isoscalar K-meson current $J_\mu{}^{(K)}$ in the form

$$J_\mu{}^{(Y)}=J_\mu{}^{(N)}+J_\mu{}^{(K)}+\text{other fields}\,, \tag{B3}$$

$$J_\mu{}^{(B)}=J_\mu{}^{(N)}+\text{other fields}. \tag{B4}$$

The Y and B mesons interact through an interaction Hamiltonian $H_{\text{int}}{}^{(1)}$ given by

$$\begin{aligned}(2/\sqrt{3})H_{\text{int}}{}^{(1)}&=f_YY_\mu J_\mu{}^{(Y)}+f_BB_\mu J_\mu{}^{(B)}\\&=(f_YY_\mu+f_BB_\mu)J_\mu{}^{(N)}+f_YY_\mu J_\mu{}^{(K)}\\&\quad+\cdots.\end{aligned} \tag{B5}$$

In addition we assume that the Y and B mesons have derivative-type couplings to nucleons which are given by

$$\frac{2}{\sqrt{3}}H_{\text{int}}{}^{(2)}=\bar{N}\left[\frac{g_Y}{2M_N}\sigma_{\mu\nu}(\partial_\nu Y_\mu)+\frac{g_B}{2M_N}\sigma_{\mu\nu}(\partial_\nu B_\mu)\right]N. \tag{B6}$$

Upon substituting Eq. (B2) into Eqs. (B5) and (B6) and then comparing with Eqs. (A1) and (A4), we obtain

$$\begin{aligned}&f_{\omega KK}=-bf_Y\,, && f_{\phi KK}=af_Y\,,\\&f_{\omega NN}=-bf_Y+af_B\,, && f_{\phi NN}=af_Y+bf_B\,,\\&g_{\omega NN}=-bg_Y+ag_B\,, && g_{\phi NN}=ag_Y+bg_B\,.\end{aligned} \tag{B7}$$

We may now obtain the amplitudes and cross sections for $p\bar{p}\to K\bar{K}$ from those of $p\bar{p}\to\pi^+\pi^-$ by making the substitutions indicated in Eq. (II.6). These substitutions may be written in terms of Y- and B-meson coupling constants as

$$\begin{aligned}\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{f}_{\rho NN}\to&\pm\tfrac{1}{4}\bar{f}_{\rho KK}\bar{f}_{\rho NN}+\tfrac{3}{4}\bar{f}_Y{}^2(W^2-m_\rho{}^2)\\&\times\left[\frac{a^2}{W^2-m_\phi{}^2}+\frac{b^2}{W^2-m_\omega{}^2}\right.\\&\left.+ab\frac{f_B}{f_Y}\left(\frac{1}{W^2-m_\phi{}^2}-\frac{1}{W^2-m_\omega{}^2}\right)\right],\end{aligned} \tag{B8a}$$

$$\begin{aligned}\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{g}_{\rho NN}\to&\pm\tfrac{1}{4}\bar{f}_{\rho KK}\bar{g}_{\rho NN}+\tfrac{3}{4}\bar{f}_Y\bar{g}_Y(W^2-m_\rho{}^2)\\&\times\left[\frac{a^2}{W^2-m_\phi{}^2}+\frac{b^2}{W^2-m_\omega{}^2}\right.\\&\left.+ab\frac{g_Y}{g_B}\left(\frac{1}{W^2-m_\phi{}^2}-\frac{1}{W^2-m_\omega{}^2}\right)\right],\end{aligned} \tag{B8b}$$

where the $+$ sign is to be taken for K^+K^- production and the minus sign is to be taken for $K^0\bar{K}^0$ production.

We define a mass, intermediate between the mass of the ϕ and the mass of the ω, by

$$m_\phi{}^2=m^2+\delta m^2\,,\quad m_\omega{}^2=m^2-\delta m^2\,, \tag{B9}$$

and expand the ω and ϕ propagators to lowest order in $\delta m^2/(W^2-m^2)$.

$$(W^2-m_\phi{}^2)^{-1}=(W^2-m^2)^{-1}+\delta m^2(W^2-m^2)^{-2}+\cdots, \tag{B10a}$$

$$(W^2-m_\omega{}^2)^{-1}=(W^2-m^2)^{-1}-\delta m^2(W^2-m^2)^{-2}+\cdots. \tag{B10b}$$

Then let $u=(W^2-m_\rho{}^2)/(W^2-m^2)$ and substitute Eq. (B10) into Eq. (B8). The latter now takes the form

$$\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{f}_{\rho NN}\to\tfrac{1}{4}\bar{f}_Y{}^2(\pm1+3u)+O\left(\frac{\delta m^2}{W^2-m^2}\right), \tag{B11a}$$

$$\tfrac{1}{2}\bar{f}_{\rho\pi\pi}\bar{g}_{\rho NN}\to\tfrac{1}{4}\bar{f}_Y(\pm\bar{g}_{\rho NN}+3u\bar{g}_Y)+O\left(\frac{\delta m^2}{W^2-m^2}\right). \tag{B11b}$$

Equations (B11) show that to lowest order, the results for $K\bar{K}$ production are independent of the mixing parameters a and b. This may be interpreted physically by noting that since the B meson does not couple to the $K\bar{K}$ current, it is only the Y meson which is a possible intermediate state, and the ω- and ϕ-meson contributions add up to the contribution of the Y meson no matter how much mixing there is.

It is now a simple matter to make the substitutions indicated by Eqs. (B11) in Eq. (II.5) and to obtain the forms of Eq. (II.7).