

ϕ -meson production in proton-proton collisionsK. Nakayama,^{1,2} J. W. Durso,^{1,3} J. Haidenbauer,¹ C. Hanhart,^{1,4,5} and J. Speth¹¹*Institut für Kernphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*²*Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602*³*Physics Department, Mount Holyoke College, South Hadley, Massachusetts 01075*⁴*Institut für Theoretische Kernphysik, Universität Bonn, D-53115 Bonn, Germany*⁵*Department of Physics and INT, University of Washington, Seattle, Washington 98195**

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The production of ϕ mesons in proton-proton collisions is investigated within a relativistic meson-exchange model of hadronic interactions. The experimental prerequisites for extracting the $NN\phi$ coupling strength from this reaction are discussed. In the absence of a sufficient set of data, which would enable an accurate determination of the $NN\phi$ coupling strength, we perform a combined analysis, based on some reasonable assumptions, of the existing data for both ω - and ϕ -meson production. We find that the recent data from the DISTO Collaboration on the angular distribution of the ϕ meson indicate that the $NN\phi$ coupling constant is small. The analysis yields values for $g_{NN\phi}$ that are compatible with the Okubo-Zweig-Iizuka rule.

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I. INTRODUCTION

The investigation of ϕ -meson production in both hadronic [1–15] and electromagnetic [16,17] processes at low and intermediate energies has attracted much attention in recent years. A major motivation for these studies is the hope that one can obtain information about the amount of hidden strangeness in the nucleon. Indications for a possibly significant $\bar{s}s$ component in the nucleon have been found, among others, in the analysis of the so-called $\pi N \Sigma$ term [18] and from the EMC measurement of deep inelastic polarized μp scattering (“nucleon-spin crisis”) [19].

In the context of ϕ -meson production processes one expects [20,21] that a large amount of hidden strangeness in the nucleon would manifest itself in reaction cross sections that significantly exceed the values estimated from the Okubo-Zweig-Iizuka (OZI) rule [22]. This phenomenological rule states that reactions involving disconnected quark lines are forbidden. In the naive quark model the nucleon has no $\bar{s}s$ content, whereas the ϕ meson is an ideally mixed pure $\bar{s}s$ state. Thus, in this case, the OZI rule implies vanishing nucleon-nucleon- ϕ ($NN\phi$) coupling and, accordingly, a negligibly small production of ϕ mesons from nucleons (or antinucleons) by electromagnetic or (nonstrange) hadronic probes. In practice there is a slight deviation from ideal mixing of the vector mesons, which means that the ϕ meson has a small $\bar{u}u + \bar{d}d$ component. Thus, even if the OZI rule is strictly enforced, there is a nonzero coupling of the ϕ to the nucleon, although the coupling is very small. Its value can be used to calculate lower limits for corresponding cross sections. For example, under similar kinematic conditions to cancel out phase space effects, one expects cross section ratios of reactions involving the production of a ϕ and an ω meson, respectively, to be [23]

$$R = \frac{\sigma(A+B \rightarrow \phi X)}{\sigma(A+B \rightarrow \omega X)} \approx \tan^2(\alpha_V), \quad (1)$$

where A , B , and X are systems that do not contain strange quarks. Here, $\alpha_V \equiv \theta_V - \theta_{V(\text{ideal})}$ is the deviation from the ideal $\omega - \phi$ mixing angle. With the value $\alpha_V \approx 3.7^\circ$ [24] one gets the rather small ratio of $R = 4.2 \times 10^{-3}$.

Recent experiments on antiproton-proton ($\bar{p}p$) annihilation at rest at the LEAR facility at CERN revealed, however, considerably larger branching ratios for various ϕ production channels [1–3]. Many of the measured ratios $\sigma(\bar{p}p \rightarrow \phi X) / \sigma(\bar{p}p \rightarrow \omega X)$ are about 100×10^{-3} or even larger (cf. the compilation of data given in Ref. [7]), which means that they exceed the estimate from the OZI rule by more than one order of magnitude. Significant deviations from the OZI rule were also found in the reactions $\bar{p}p \rightarrow \phi\phi$ [4] and $p d \rightarrow {}^3\text{He}\phi$ [5].

These observed large ϕ -production cross sections were interpreted by some authors as a clear signal for an intrinsic $\bar{s}s$ component in the nucleon [7,8]. However, this explanation is still controversial. There is an alternative approach aimed at understanding these large cross sections solely by the strong rescattering effects in the final state [9–12]. In this case ϕ production occurs via two-step processes with intermediate states such as $\bar{K}K$, $\bar{K}K^*$, $\bar{\Lambda}\Lambda$, etc., where each step is allowed by the OZI rule. Corresponding quantitative calculations have, indeed, demonstrated that the resulting production cross sections are sufficiently large to agree with the experiments without a violation of the OZI rule [9–12].

In this connection, the production of ϕ mesons in proton-proton (pp) collisions is of special interest. In principle, the production cross section can be used for a direct determination of the $NN\phi$ coupling strength. Any appreciable $NN\phi$ coupling in excess of the value given by the OZI rule could be seen as evidence for hidden strangeness in the nucleon. Of course, there is also an alternative picture: one in which the

*Present address.

coupling of the ϕ meson to the nucleon does not occur via possible $\bar{s}s$ components in the nucleon, but via intermediate states with strangeness [25,26]. Specifically, this means that the ϕ meson couples to the nucleon via virtual ΛK , ΣK , etc. states. Corresponding model calculations have shown, however, that such processes give rise to (effective) $NN\phi$ coupling constants comparable to the OZI values and therefore should not play a role in drawing conclusions concerning hidden strangeness in the nucleon. Accordingly, one expects that cross section ratios $\sigma(pp \rightarrow pp\phi)/\sigma(pp \rightarrow pp\omega)$ should provide a clear sign for a possible OZI violation. Indeed, data presented recently by the DISTO Collaboration [6] indicate that this ratio, after correcting for the phase space effects, is about eight times larger than the OZI estimate (1).

The present work focuses on the $pp \rightarrow pp\phi$ process. We discuss the experimental prerequisites that would enable one to disentangle competing reaction mechanisms for ϕ production in nucleon-nucleon (NN) collisions and to extract the value of the $NN\phi$ coupling strength. In this context we shall show that the angular distribution of the produced ϕ mesons plays a crucial role. In particular, we will demonstrate that the almost isotropic angular distribution seen in the data from the DISTO Collaboration [6] indicates that the $NN\phi$ coupling is very small. In the absence of a set of data sufficient to permit an accurate determination of the $NN\phi$ coupling strength, we impose certain reasonable assumptions and carry out a combined analysis of the recent ϕ -meson production data of the DISTO Collaboration [6] and the data of ω -meson production from SATURNE [27]. This analysis yields a range of values for $g_{NN\phi}$ that is compatible with the OZI rule.

We describe the $pp \rightarrow pp\phi$ reaction within a relativistic meson-exchange model. (See Ref. [28] for the details of the formalism.) The transition amplitude is calculated in distorted wave Born approximation, where the NN final state interaction is taken into account explicitly. The final state interaction is known to be very important at near-threshold energies. For the NN interaction we employ the model Bonn B as defined in Table A.1 of Ref. [29]. This model reproduces the NN phase shifts up to the pion-production threshold as well as the deuteron properties [29]. As in our previous work [28], we do not consider the initial state interaction explicitly. At the corresponding high incident energies the NN interaction is a slowly varying function of energy. Its main effect is to lead to an overall reduction of the $pp \rightarrow pp\phi$ cross section [30], as has been shown explicitly for the case of the reaction $pp \rightarrow pp\eta$ by Batinić *et al.* [31]. In the present model this effect of the initial state interaction is accounted for by an appropriate adjustment of the (phenomenological) form factors at the hadronic vertices.

In the next section we discuss possible basic production currents that can contribute to the reaction $pp \rightarrow pp\phi$. Using SU(3) flavor symmetry and imposing the OZI rule, we calculate meson-meson-meson and nucleon-nucleon-meson coupling constants that are relevant for the ϕ -production currents and then estimate the corresponding contributions to the total cross section. These reveal that the $\phi\rho\pi$ meson-exchange current is the dominant one. In the same section we

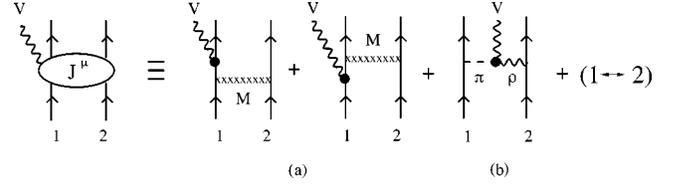


FIG. 1. ϕ and ω -meson production currents, J^μ , included in the present study: (a) nucleonic current, (b) meson exchange current. $v = \omega, \phi$ and $M = \pi, \eta, \rho, \omega, \sigma, a_0$.

also give a short outline of our formalism and introduce the free parameters of our model. In Sec. III we describe in detail the procedure for the combined analysis of ϕ - and ω -production data. We conclude with a summary of our results in the last section.

II. PRODUCTION CURRENTS

In the case of the reaction $pp \rightarrow pp\omega$, the dominant production mechanisms —namely, the nucleonic and $\omega\rho\pi$ mesonic currents, as depicted in Fig. 1—can be identified without involved considerations. This is because of the relatively large $NN\omega$ and $\omega\rho\pi$ coupling strengths. The $\omega\rho\pi$ meson-exchange current depends also on the $NN\rho$ and $NN\pi$ couplings, which are likewise large. Therefore this production mechanism is by far the dominant one among the possible exchange currents [28]. For ϕ -meson production, however, the situation is much less clear *a priori* and requires careful consideration. In order to determine the importance of various possible meson-exchange currents, we first estimate systematically the coupling strengths of the hadronic vertices that enter into these ϕ -production exchange currents. This is done using effective Lagrangians, assuming SU(3) flavor symmetry, and imposing the OZI rule. We note that in this scheme the SU(3) symmetry breaking is introduced through the use of the physical masses of the hadrons in calculating the observables.

In the present work we are interested in three-meson vertices involving at least one ϕ -meson. We, then, have VVP , VPP , and VVV vertices ($V =$ vector meson, $P =$ pseudo-scalar meson). The SU(3) effective Lagrangian has the form

$$\begin{aligned} \mathcal{L}_{MMM} = & g_{888} [-(1-\beta) \text{Tr}([M_8, M_8] M_8) \\ & + \beta \text{Tr}(\{M_8, M_8\} M_8)] + g_{88s} \beta \text{Tr}(\{M_8, M_8\} M_s) \\ & + g_{8s8} \beta \text{Tr}(\{M_8, M_s\} M_8) \\ & + g_{sss} \beta \text{Tr}(\{M_s, M_s\} M_s), \end{aligned} \quad (2)$$

where M_8 (M_s) stands for the SU(3) meson-octet (-singlet) matrix, and β is the parameter specifying the admixture of the D -type ($\beta=1$) and F -type ($\beta=0$) couplings. The OZI condition relates the basic coupling constants of the SU(3) octet and singlet members in the Lagrangian, $g_{sss} = g_{88s} = g_{8s8} = \sqrt{\frac{2}{3}} g_{888}$, so that there is only one free coupling constant. This one is then fixed by a fit to some appropriate observables such as decay rates. The VPP and VVV vertices involve only F -type coupling if we require charge conjuga-

TABLE I. SU(3) based estimate of the ϕVP coupling constants, $g_{\phi VP}$ at the vanishing four-momentum square of the vector-meson V . The coupling constants are given in units of $1/\sqrt{m_\phi m_V}$, with m_V denoting the mass of the vector-meson V involved. The parameters of the SU(3) effective Lagrangian are taken from Ref. [32] (model B).

| $g_{\phi\rho\pi}$ | $g_{\phi\phi\eta}$ | $g_{\phi\omega\eta}$ | $g_{\phi\phi\eta'}$ | $g_{\phi\omega\eta'}$ |
|-------------------|--------------------|----------------------|---------------------|-----------------------|
| -0.65 | 9.86 | 0.19 | -9.80 | -1.11 |

tion invariance. This leads to the vanishing of all VPP and VVV couplings involving either the ω or ϕ meson relevant to the present work. The D -type coupling leads to G -parity violating vertices and will be ignored. In contrast, the VVP vertices involve only D -type coupling. In Ref. [32] essentially the same scheme as proposed here has been used to describe radiative meson decays. Therefore, we use the model parameters determined in that paper. The effective Lagrangian used in Ref. [32] can easily be cast into the form given by Eq. (2). The resulting coupling constants g_{VVP} at those vertices relevant for the meson-exchange currents of interest are tabulated in Table I.

In order to estimate the magnitude of the various meson-exchange currents one needs not only the VVP couplings, but the corresponding NNV and NNP couplings as well. Thus, in addition to the $NN\pi$ and $NN\rho$ couplings, the empirically poorly known $NN\omega$, $NN\phi$, $NN\eta$, and $NN\eta'$ couplings are needed. We estimate these coupling strengths using the same scheme used for determining the VVP couplings, i.e., the SU(3) effective Lagrangian

$$\mathcal{L}_{BBM} = g_8[-(1-\beta)\text{Tr}(\{\bar{B}, B\}M_8) + \beta\text{Tr}(\{\bar{B}, B\}M_8)] + g_s\beta\text{Tr}(\{\bar{B}, B\}M_s), \quad (3)$$

plus the OZI rule. This latter condition yields $g_s = (3 - 4\beta)g_8/\sqrt{6}$. In the above Lagrangian B stands for the SU(3) baryon-octet matrix. The D -type coupling in the SU(3) Lagrangian is not allowed for the NNV couplings if one requires spin independence for $BB\omega$ and $BB\phi$ couplings within the identically flavored baryons, $B = \Sigma, \Lambda$. Using the value of the $\omega - \phi$ mixing angle from Ref. [24] and g_8 ($= g_{NN\rho}$) from Ref. [29], we find $g_{NN\omega} \cong 9$ and $g_{NN\phi} \cong -0.6$ for the $NN\omega$ and $NN\phi$ vector-coupling constants, respectively. The NNV tensor-coupling constants are simply chosen to be $f_{NNV} = \pm 0.5 g_{NNV}$, where $v = \omega, \phi$ (as distinct from V , which stands for vector mesons in general). This choice of f_{NNV} is consistent with values from an SU(3) estimate [33] as well from other sources [26,29]. For the $NN\eta$ coupling constant we take the value used in NN scattering analysis [29], $g_{NN\eta} = 6.14$. This value, together with the $\eta - \eta'$ mixing angle of $\theta_p \cong -9.7^\circ$, as suggested by the quadratic mass formula, and the $NN\pi$ coupling constant, $g_{NN\pi} = 13.45$, leads to the ratio $D/F \equiv \beta/(1-\beta) \cong 1.43$ - which is close to the value of $D/F = 1.58 \pm 0.07$ extracted from a systematic analysis of semileptonic hyperon decays [34]. The $NN\eta'$ coupling constant is related to the $NN\eta$ coupling constant by $g_{NN\eta'} = -g_{NN\eta}\tan(\alpha_p)$, where $\alpha_p \equiv \theta_p - \theta_{P(\text{ideal})}$

$\cong -45^\circ$ denotes the deviation from the pseudoscalar ideal mixing angle. We find $g_{NN\eta'} \cong 6.1$.

Once all the relevant coupling constants have been determined, we can estimate the relative importance of various VVP -exchange currents to the ϕ -meson production. In corresponding test calculations it turned out that the $\phi\rho\pi$ -exchange current is by far the dominant mesonic current. The *combined* contribution of all other exchange currents to the total cross section is about two orders of magnitude smaller.

We have also examined contributions from meson-exchange currents involving other heavy mesons, in particular, the $\phi\phi f_1$ - and $\phi\omega f_1$ -exchange currents, whose coupling constants (upper limits) can be estimated from the observed decay of $f_1 \rightarrow \phi + \gamma$ [24]. We find a negligible contribution to the ϕ -meson production. Furthermore the $\phi\phi\sigma$ - and $\phi\omega\sigma$ -exchange currents also turned out to be negligible. Finally we note that, as in the case of ω production, there are no experimental indications of any of the known isospin-1/2 N^* resonances decaying into $N\phi$.

With the above considerations, the v -meson ($v = \omega, \phi$) production current J^μ is given by the sum of the nucleonic and $v\rho\pi$ meson-exchange currents, $J^\mu = J_{nuc}^\mu + J_{mec}^\mu$, as illustrated diagrammatically in Fig. 1. Explicitly, the nucleonic current is defined as

$$J_{nuc}^\mu = \sum_{j=1,2} (\Gamma_j^\mu iS_j U + U iS_j \Gamma_j^\mu), \quad (4)$$

with Γ_j^μ denoting the NNv vertex and S_j the nucleon (Feynman) propagator for nucleon j . The summation runs over the two interacting nucleons, 1 and 2. U stands for the meson-exchange NN potential. It is, in principle, identical to the driving potential used in the construction of the NN interaction [29], except that here meson retardation effects are retained following the Feynman prescription. Equation (4) is illustrated in Fig. 1(a).

The structure of the NNV vertex, Γ_j^μ , required in Eq. (4) for the production is obtained from the Lagrangian density

$$\mathcal{L}(x) = -\bar{\Psi}(x) \left(g_{NNv} \left[\gamma_\mu - \frac{\kappa_v}{2m_N} \sigma_{\mu\nu} \partial^\nu \right] V^\mu(x) \right) \Psi(x), \quad (5)$$

where $\Psi(x)$ and $V^\mu(x)$ stand for the nucleon and vector-meson field, respectively. g_{NNv} denotes the vector coupling constant and $\kappa_v \equiv f_{NNv}/g_{NNv}$, with f_{NNv} the tensor coupling constant. m_N denotes the nucleon mass.

As in most meson-exchange models of interactions, each hadronic vertex is furnished with a form factor in order to account for, among other things, the composite nature of the hadrons involved. In this spirit the NNV vertex obtained from the above Lagrangian is multiplied by a form factor. The theoretical understanding of this form factor is beyond the scope of the present paper; we assume it to be of the form

$$F_{vNN}(l^2) = \frac{\Lambda_{NV}^4}{\Lambda_{NV}^4 + (l^2 - m_N^2)^2}, \quad (6)$$

where l^2 denotes the four-momentum squared of either the incoming or outgoing off-shell nucleon. It is normalized to unity when the nucleon is on its mass shell, i.e., when $l^2 = m_N^2$.

The $\nu\rho\pi$ vertex required for constructing the meson-exchange current, J_{mec}^μ [Fig. 1(b)], is derived from the Lagrangian density

$$\mathcal{L}_{\nu\rho\pi}(x) = \frac{g_{\nu\rho\pi}}{\sqrt{m_\nu m_\rho}} \varepsilon_{\alpha\beta\nu\mu} \partial^\alpha \vec{\rho}^\beta(x) \cdot \partial^\nu \vec{\pi}(x) V^\mu(x), \quad (7)$$

where $\varepsilon_{\alpha\beta\nu\mu}$ denotes the Levi-Civita antisymmetric tensor with $\varepsilon_{0123} = +1$. The $\nu\rho\pi$ vertex obtained from the above Lagrangian is multiplied by a form factor which is taken to be of the form

$$F_{\nu\rho\pi}(q_\rho^2, q_\pi^2) = \left(\frac{\Lambda_{M_V}^2 - x m_\rho^2}{\Lambda_{M_V}^2 - q_\rho^2} \right) \left(\frac{\Lambda_{M_V}^2 - m_\pi^2}{\Lambda_{M_V}^2 - q_\pi^2} \right). \quad (8)$$

It is normalized to unity at $q_\pi^2 = m_\pi^2$ and $q_\rho^2 = x m_\rho^2$. The parameter x ($= 0$ or 1) is introduced in order to allow for different normalization points as explained later. The form factor given above differs from the one used in [28] in that it uses a common cutoff parameter Λ_{M_V} for both π and ρ meson instead of separate cutoff masses.

The meson-exchange current is then given by

$$J_{mec}^\mu = [\Gamma_{NN\rho}^\alpha(q_\rho)]_1 i D_{\alpha\beta}(q_\rho) \Gamma_{\nu\rho\pi}^{\beta\mu}(q_\rho, q_\pi, k_\nu) i \Delta(q_\pi) \times [\Gamma_{NN\pi}(q_\pi)]_2 + (1 \leftrightarrow 2), \quad (9)$$

where $D_{\alpha\beta}(q_\rho)$ and $\Delta(q_\pi)$ stand for the ρ - and π -meson (Feynman) propagators, respectively. The vertices Γ involved are self-explanatory. Both the $NN\rho$ and $NN\pi$ vertices, $\Gamma_{NN\rho}^\alpha$ and $\Gamma_{NN\pi}$, are taken consistently with the NN potential used to generate the NN final state interaction.

Our model for vector-meson production described above contains five parameters: two for the mesonic current (the coupling constant $g_{\nu\rho\pi}$ and the cutoff parameter Λ_{M_V}) and three for the nucleonic current (the coupling constants g_{NNV} and f_{NNV} , and the cutoff parameter Λ_{NV}). In Ref. [28] we pointed out that the angular distribution of the emitted ω mesons is a sensitive quantity for determining the *absolute amount* of nucleonic as well as mesonic current contributions, in addition to the relative sign between the two contributions. This applies also to the case of ϕ -meson production since, as we have argued above, the dominant production mechanisms are exactly the same for both processes. Specifically, this means that the knowledge of the angular distribution allows one to fix the cutoff parameter in the mesonic current since the coupling constant $g_{\nu\rho\pi}$ can be extracted from the relevant measured partial decay widths [24].

The nucleonic current, however, involves three free parameters. In this case knowledge of the angular distribution allows one to determine only the product of the NNV coupling constants and the form factor. Consequently one cannot extract a unique value for g_{NNV} directly from the analysis; further constraints—such as the energy dependence of the angular distribution—are needed. As discussed in [28], the

energy dependence will impose some constraint on the form factor. Also, in the energy region far from the threshold, the tensor-to-vector coupling ratio $\kappa_V = f_{NNV}/g_{NNV}$ influences the energy dependence of the total cross section. Another constraint may be imposed by spin polarization observables. In the case of pp bremsstrahlung producing hard photons, it is known that the reaction is dominated by the magnetization current, to which the tensor coupling of the $NN\gamma$ vertex contributes. Therefore we would expect that the spin observables in $pp \rightarrow ppV$ reactions become more sensitive to the tensor coupling f_{NNV} for energetic vector mesons.

III. APPLICATION

As mentioned in the Introduction, the determination of the $NN\phi$ coupling strength is of special interest in the study of vector-meson production since its magnitude is usually associated with the amount of hidden strangeness in the nucleon. In this section we utilize our model to obtain some information on this coupling strength. However, as pointed out in the previous section, the angular distribution alone is not sufficient for determining $g_{NN\phi}$ uniquely. We therefore choose to perform a combined analysis of ϕ - and ω -meson production; i.e., to use the available data from both reactions to extract $g_{NN\phi}$. A combined analysis of ϕ and ω production also allows us to address the important issue concerning the violation of the OZI rule.

Before doing so some considerations about the existing experimental data are in order. So far only very few precision data of vector-meson production in NN collisions are available. First there are total cross sections for the reaction $pp \rightarrow pp\omega$ in the energy range $T_{lab} \cong 1.89$ to 1.98 GeV from Saclay [27]. In addition, there are angular distributions of the emitted meson for both ω - and ϕ -meson production (although with no absolute normalization) and the ratio of the total cross sections $\sigma_\phi/\sigma_\omega \equiv \sigma(pp \rightarrow pp\phi)/\sigma(pp \rightarrow pp\omega)$ at $T_{lab} = 2.85$ GeV from the DISTO Collaboration [6]. All the other presently available data [35] are from the 1970's and not very accurate. Furthermore these data lie in an energy range far above the vector-meson production thresholds. At the corresponding excess energies the NN interaction in the final state is already dominated by inelastic processes. Such processes are not accounted for in the NN model that we employ, which is valid only for energies below the pion-production threshold (i.e., excess energies below ≈ 140 MeV), and therefore we do not consider those high-energy data in our analysis. Since the excess energy in the ω -meson production channel of the DISTO measurement ($Q = 319$ MeV) is already beyond the energy range where we trust our model, we do not use the measured production ratio directly. Instead we interpolate the total cross section for ω -meson production from the existing data [27,35] and use this value, and the measured ratio, to fix the absolute normalization of the measured ϕ -meson angular distribution [6]. Our estimate yields $\sigma_\omega \sim 0.7 \times 10^2 \mu\text{b}$ at $T_{lab} = 2.85$ GeV. This value of σ_ω , combined with the measured ratio of $\sigma_\phi/\sigma_\omega = (3.7 \pm 0.5) \times 10^{-3}$ [6], leads to $\sigma_\phi \sim 0.26 \mu\text{b}$. Inevitably, such an interpolation is subject to uncertainties. We have, therefore, carried out the same analy-

sis as reported below, but starting from a ϕ -production cross section that is smaller/larger by about 40%. We arrived at basically the same conclusions and therefore refrain from showing the corresponding results here.

Since we have one ϕ -meson angular distribution with only nine data points and five ω -meson total cross section data available in the range of applicability of our model, we are forced to impose some constraints on the model in order to reduce the number of free parameters. To this end we make the following assumptions.

(1) The same cutoff parameter $\Lambda_M \equiv \Lambda_{M\omega} = \Lambda_{M\phi}$ [cf. Eq. (8)] is used for the meson-exchange currents for ω - and ϕ -meson production. This is a reasonable choice since the off-shell particles at the $\nu\rho\pi$ vertex are the same in both production processes. Likewise, the cutoff parameter Λ_{NV} [cf. Eq. (6)] in the nucleonic current is assumed to be the same for ω - and ϕ -meson production, i.e., $\Lambda_N \equiv \Lambda_{N\omega} = \Lambda_{N\phi}$.

(2) The $NN\omega$ vector coupling constant is given by the value obtained from SU(3) flavor symmetry and imposing the OZI rule, i.e., $g_{NN\omega} = 3g_{NN\rho}\cos(\alpha_V)$, where $\alpha_V \equiv \theta_V - \theta_{V(ideal)}$ is the deviation from the ideal ω - ϕ mixing angle. With $\alpha_V \approx 3.7^\circ$ [24] and the $NN\rho$ coupling constant of $g_{NN\rho} = 2.3 - 3.36$ [36], this yields a value of $g_{NN\omega} \approx (9 \pm 2)$, which is close to the value of $g_{NN\omega} \approx 11$ obtained in a recent NN scattering analysis [37]. The uncertainty here comes from the uncertainties involved in $g_{NN\rho}$ and α_V .

(3) The tensor-to-vector coupling ratio, $\kappa_V = f_{NNV}/g_{NNV}$, is the same for the ω and ϕ mesons: $\kappa \equiv \kappa_\omega = \kappa_\phi$. This relation is also suggested by SU(3) symmetry. Furthermore we choose the parameter κ to be fixed beforehand. We consider the values $\kappa = \pm 0.5$, which covers a rather ample range. Unlike the case of the ρ meson, we do not expect $f_{NNV} = \kappa_V g_{NNV}$ to be large, especially for the ω meson. This is supported by an estimate [33], in which SU(3) is applied to the sum $f_{NNV} + g_{NNV}$ rather than to f_{NNV} alone, which is motivated by the success of SU(6) in predicting the magnetic moments of the baryons. Other investigations [26,29] also support small values of κ_V .

These assumptions reduce the number of parameters of the model to be fixed to a total of five: the cutoff parameters Λ_M and Λ_N , and the coupling constants $g_{\phi\rho\pi}$, $g_{\omega\rho\pi}$, and $g_{NN\phi}$. As mentioned in the previous section, the first two coupling constants can be extracted from the measured branching ratios. Specifically, the coupling constant of $g_{\phi\rho\pi} = -1.64$ is determined directly from the measured decay width of $\phi \rightarrow \rho + \pi$ [24]. The coupling constant $g_{\omega\rho\pi}$, however, cannot be determined directly (as in the case of $g_{\phi\rho\pi}$) since $\omega \rightarrow \rho + \pi$ is energetically forbidden. We therefore extract it indirectly from the radiative decay width of $\omega \rightarrow \pi + \gamma$, assuming vector meson dominance; we obtain $g_{\omega\rho\pi} = 10$. The signs of these couplings are inferred from SU(3) symmetry considerations. We note that these coupling constants are extracted at different kinematics: $g_{\phi\rho\pi}$ is determined at $q_\rho^2 = m_\rho^2$ and $q_\pi^2 = m_\pi^2$, whereas $g_{\omega\rho\pi}$ is extracted at $q_\rho^2 = 0$ and $q_\pi^2 = m_\pi^2$. The corresponding form factor [cf. Eq. (8)] should, therefore, be normalized accordingly, i.e., $x=1$ and $x=0$ for the $\phi\rho\pi$ and $\omega\rho\pi$ vertex form factor, respec-

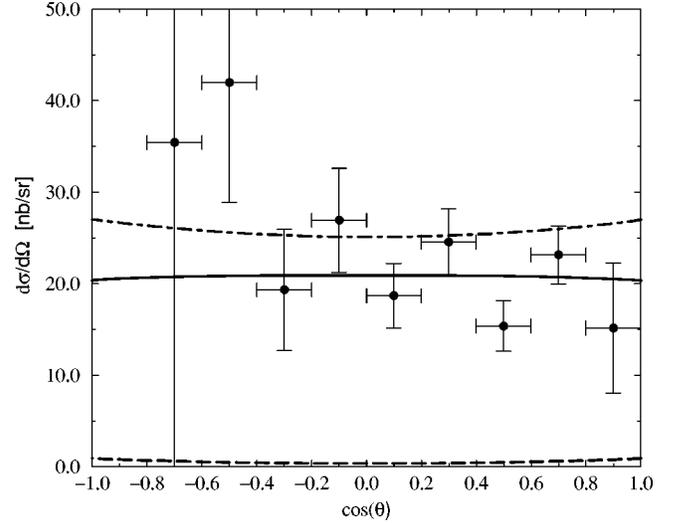


FIG. 2. Angular distribution for the reaction $pp \rightarrow pp\phi$ at an incident energy of $T_{lab} = 2.85$ GeV. The dashed-dotted curve corresponds to the mesonic current contribution, the dashed curve to the nucleonic current contribution. The solid curve is the total contribution. The experimental data are from Ref. [6] and have been normalized according to the procedure explained in the text. The identity of the two initial particles requires the angular distribution to be symmetric about $\cos(\theta) = 0$. An even polynomial fit to the data yields a curve almost identical to the total contribution.

tively. With the coupling constants at the three-meson-point vertices fixed, we are then left with three free parameters which may be adjusted to reproduce the ϕ - and ω -meson production data.

The process of reducing to these three so that we can extract some information about the ϕ -nucleon coupling has a cost. A least squares fit of the remaining parameters to the data would now be statistically meaningless, so that we will be unable to assign a single number with appropriate confidence limits to $g_{NN\phi}$. Rather, our results will be presented so as to show a range of possibilities consistent with the assumptions underlying the model and the analysis. This is unfortunate, but the scarcity of the data and the relatively large number of model parameters excluded the possibility of a full statistical analysis from the outset.

We are now prepared to apply the model to the reactions $pp \rightarrow pp\omega$ and $pp \rightarrow pp\phi$. Before doing any calculation, however, we note that the nucleonic current contribution to the ϕ -meson production should be rather small, as the measured angular distribution shown in Fig. 2 is more or less isotropic. Recall that the angular distribution alone is sufficient to establish the magnitude of both the nucleonic and mesonic currents, and that the mesonic current yields a nearly flat angular distribution, whereas the nucleonic current gives an approximately $\cos^2(\theta)$ dependence [28], although at the scale of Fig. 2 this latter feature of the nucleonic current is difficult to see.

For the determination of the free parameters Λ_M , Λ_N , and $g_{NN\phi}$ we proceed in the following way: we assume that the angular distribution of the ϕ meson resembles the solid curve in Fig. 2. We then determine the required contributions from both the nucleonic and mesonic currents. The mesonic

TABLE II. $NN\phi$ coupling constant extracted from our model analysis of the reaction $pp \rightarrow ppv$ ($v = \phi, \omega$) as described in Sec. III for two given values of the ratio $\kappa = f_{NNv}/g_{NNv}$.

| κ | -0.5 | -0.5 | +0.5 | +0.5 |
|--------------|-------|-------|-------|-------|
| Λ_N | 1170 | 1411 | 1312 | 1545 |
| $g_{NN\phi}$ | -0.45 | -0.19 | -0.90 | -0.40 |

current involves only one free parameter: namely the cutoff mass Λ_M ($\equiv \Lambda_{M\phi} = \Lambda_{M\omega}$) of the $\phi\rho\pi$ vertex form factor [cf. Eq. (8)]. That is fixed by the requirement of reproducing the angular distribution. We obtain $\Lambda_M = 1450$ MeV. Turning now to ω production, we require that our model describe the total cross section data from SATURNE [27]. Since we assumed the $NN\omega$ vector coupling to be $g_{NN\omega} = 9$ (and $\kappa \equiv \kappa_\omega = \kappa_\phi$ is fixed to the two values mentioned above), one can determine the cutoff parameter Λ_N ($\equiv \Lambda_{N\omega} = \Lambda_{N\phi}$) in Eq. (6)—the only remaining free parameter—from the ω -production cross section. Owing to the destructive interference between the nucleonic and mesonic currents, we find, in general, two possible values of Λ_N for given $g_{NN\omega}$ and κ . The resulting values are listed in Table II and the corresponding cross sections are shown in Fig. 3. As pointed out in [28], in contrast to the angular distribution, the total cross section is unable to constrain the absolute contribution of the nucleonic and mesonic currents. As can be seen from Fig. 3, the energy dependence of the total cross section may be useful to further constrain the ratio κ and/or the form factor at the production vertex. Unfortunately, no data is available at energies that are well above the threshold, yet still low enough for the present model to be applicable. It should be mentioned that effects of the finite width of the ω meson—

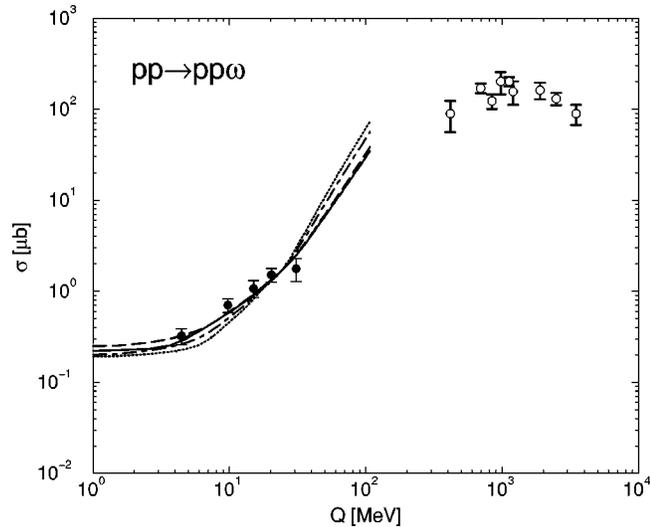


FIG. 3. Total cross section for the reaction $pp \rightarrow pp\omega$ as a function of the excess energy $Q = \sqrt{s} - \sqrt{s_0}$. The dotted, dash-dotted, dashed, and solid lines correspond to the model calculation based on the cutoff mass of $\Lambda_N = 1545, 1312, 1411,$ and 1170 MeV, respectively, as given in Table II. Effects of the ω -meson mass distribution are taken into account. The experimental data are from Ref. [27] (filled circle) and from Ref. [35] (open circle).

which influence considerably the energy dependence of the total cross section close to the threshold energy [38]—have been taken into account in the results shown in Fig. 3. This is done by folding the calculated cross section with the Breit-Wigner mass distribution of the ω meson. Once the cutoff parameter Λ_N is fixed, one can return to the angular distribution of the ϕ -meson production in Fig. 2 and adjust the $NN\phi$ coupling constant $g_{NN\phi}$ to reproduce the amount of the nucleonic current contribution previously determined. Since we have two values of Λ_N for each chosen value of κ , we get four values of $g_{NN\phi}$ corresponding to the four possible combinations. The values for the $NN\phi$ coupling constant thus extracted are compiled at the bottom of Table II. They range from $g_{NN\phi} = -0.19$ to $g_{NN\phi} = -0.90$. As already acknowledged above, the lack of a more complete and accurate set of data prevents us from achieving a more accurate determination of $g_{NN\phi}$.

The values of $g_{NN\phi}$ thus obtained may be compared with those resulting from SU(3) flavor symmetry considerations and imposition of the OZI rule,

$$g_{NN\phi} = -3g_{NN\rho}\sin(\alpha_V) \cong -(0.60 \pm 0.15), \quad (10)$$

where the factor $\sin(\alpha_V)$ is due to the deviation from the ideal $\omega - \phi$ mixing. The numerical value is obtained using the values $g_{NN\rho} = 2.63 - 3.36$ [36] and $\alpha_V \cong 3.7^\circ$ [24]. The error bar quoted is due to the uncertainty involved in $g_{NN\rho}$ and α_V . Comparing the value [Eq. (10)] with those obtained in the present work we conclude that the ϕ -production data can be described with $NN\phi$ coupling constants that are compatible with the OZI value.

Although the nucleonic current contribution to ϕ -meson production is small its effect on the angular distribution shown in Fig. 2 is actually quite strong due to its interference with the mesonic exchange current. For any of the sets of parameters shown in Table II, a doubling of $g_{NN\phi}$ would result in a decidedly poorer description of the ϕ -meson production data, especially the shape of the angular distribution.

It should be mentioned that although our analysis of the existing DISTO and SATURNE data yields $NN\phi$ coupling constants which are compatible with the OZI value, it is necessary to introduce a violation of the OZI rule at the $\nu\rho\pi$ vertices ($\nu = \phi, \omega$) in the meson-exchange current. This can easily be verified by calculating, e.g., the $\phi\rho\pi$ coupling constants at $q_\rho^2 = 0$ using the form factor given by Eq. (8) with the cutoff parameter Λ_M extracted from the ϕ -meson angular distribution data. We obtain $g_{\phi\rho\pi}(q_\rho^2 = 0) = g_{\phi\rho\pi}(q_\rho^2 = m_\rho^2) \times F_{\nu\rho\pi}(q_\rho^2 = 0, q_\pi^2) = -1.18$. This value is almost a factor of 2 larger than the corresponding OZI value of $g_{\phi\rho\pi}(q_\rho^2 = 0) = -g_{\omega\rho\pi}(q_\rho^2 = 0)\tan(\alpha_V) \cong -0.65$ given in Table I. We found it impossible to describe the data without introducing this OZI violation (independently of the considerations about the $NN\phi$ coupling constant) for the following reasons: A sufficiently large contribution from the mesonic current in the ϕ -meson production, as demanded by the measured angular distribution, can only be obtained with the $\phi\rho\pi$ coupling constant extracted from the measured decay width of $\phi \rightarrow \rho + \pi$ [24], i.e., $g_{\phi\rho\pi} = -1.64$. For the coupling constant extracted from radiative meson decay, an unrealis-

tically large cutoff mass Λ_M in excess of 3 GeV would be required. On the other hand, with $g_{\phi\rho\pi} = -1.64$ and the corresponding OZI value of $g_{\omega\rho\pi} = -g_{\phi\rho\pi}/\tan(\alpha_V) = 25$ for the $\omega\rho\pi$ coupling constant, we have little chance of describing the energy dependence of the ω meson total cross section; it simply rises much too strongly with the energy. In this context let us mention that a knowledge of the angular distribution of the ω -meson in the energy region where the model is applicable is of particular importance. Corresponding data would enable us to pin down the contributions for the mesonic current and thereby impose much more stringent constraints on the parameters of the model relevant to a possible violation of the OZI rule at the $\nu\rho\pi$ vertices. It would be very useful to clarify this point, specifically because an analysis of the radiative decay widths of the vector mesons within the vector-meson dominance model, involving the very same coupling constants, led to $\nu\rho\pi$ coupling constants which satisfy the OZI rule to within 15–20% [32]. Furthermore it is certainly desirable to test the present model in describing other independent reactions processes (e.g., ϕ - and ω -meson photoproduction). We plan such investigations in the near future.

Finally, we wish to make a remark on the “naive” OZI estimation as expressed by Eq. (1). This equation is simply a consequence of assuming that the ϕ - and ω -meson production amplitudes differ from each other only by their coupling strengths, which are assumed to be related by SU(3) flavor symmetry plus the OZI rule. Differences in the kinematics (besides trivial phase-space effects) induced, for example, by the mass difference between the ω and ϕ mesons, interference effects between the nucleonic and meson-exchange currents, etc., are completely ignored. Our model offers the possibility to test explicitly the validity of this assumption and thus the reliability of Eq. (1). For this purpose we carried out a (full) model calculation where we imposed the OZI rule to relate the relevant coupling constants; i.e., $g_{\phi\rho\pi}/g_{\omega\rho\pi} = -\tan(\alpha_V)$ and $g_{NN\phi}/g_{NN\omega} = -\tan(\alpha_V)$. In addition, we used the same form factors at the ω - and ϕ -meson production vertices in the mesonic and the nucleonic current, respectively. It turned out that such a calculation yields results

that are qualitatively very similar to the simple estimate of Eq. (1), indicating that the above-mentioned differences in the kinematics, etc., do not induce any significant deviation from Eq. (1). In fact, the cross section ratio taken at the same excess energy is roughly 3×10^{-3} , or about 30% smaller than the “naive” OZI estimate.

IV. SUMMARY

We have investigated the reaction $pp \rightarrow pp\phi$ using a relativistic meson-exchange model. We find that the nucleonic and $\phi\rho\pi$ exchange currents are the two dominant sources contributing to ϕ production in this reaction, and that they interfere destructively. Since these two reaction mechanisms give rise to distinct angular distributions, measurements of this observable can yield valuable information on the magnitude of the nucleonic current and, specifically, on the $NN\phi$ coupling constant. In fact, the flat angular distribution exhibited by the data from DISTO Collaboration [6] indicates that the contribution from the nucleonic current must be very small. This, in turn, implies that the value of the $NN\phi$ coupling constant must also be small. While we are unable, for reasons mentioned earlier, to place rigorous limits on the value of the ϕ -nucleon coupling constant, we can say that the available data might not exclude, but do not clearly require, a large strangeness content of the nucleon. Indeed, our semiquantitative combined analysis of those ϕ -meson production data and the data for ω -meson production from SATURNE yields values of $g_{NN\phi}$ which are compatible with the OZI rule.

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