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ϕ meson production in $p\bar{p}$ annihilation at rest

S. Srisuphaphon,[1] Y. Yan,[1,2] Thomas Gutsche,[3] and Valery E. Lyubovitskij[3,*]

[1]*School of Physics, Suranaree University of Technology, 111 University Avenue, Nakhon Ratchasima 30000, Thailand*
[2]*Thailand Center of Excellence in Physics, Ministry of Education, Bangkok, Thailand*
[3]*Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*

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Apparent channel-dependent violations of the Okubo-Zwieg-Iizuka (OZI) rule in nucleon-antinucleon annihilation reactions in the presence of an intrinsic strangeness component in the nucleon are discussed. Admixture of $s\bar{s}$ quark pairs in the nucleon wave function enables the direct coupling to the ϕ-meson in the annihilation channel without violating the OZI rule. Three forms are considered in this work for the strangeness content of the proton wave function, namely, the uud cluster with a $s\bar{s}$ sea-quark component, kaon-hyperon clusters based on a simple chiral quark model, and the pentaquark picture $uuds\bar{s}$. Nonrelativistic quark model calculations reveal that the strangeness magnetic moment μ_s and the strangeness contribution to the proton spin σ_s from the first two models are consistent with recent experimental data, where μ_s and σ_s are negative. For the third model, the $uuds$ subsystem with the configurations $[31]_{FS}[211]_F[22]_S$ and $[31]_{FS}[31]_F[22]_S$ leads to negative values of μ_s and σ_s. With effective quark line diagrams incorporating the ${}^3P_0$ model, we give estimates for the branching ratios of the annihilation reactions at rest $p\bar{p} \to \phi X$ ($X = \pi^0$, η, ρ^0, ω). Results for the branching ratios of ϕX production from atomic $p\bar{p}$ s-wave states are for the first and third model found to be strongly channel dependent, in good agreement with measured rates.

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I. INTRODUCTION

In the simple constituent quark model, where the proton is made of two constituent u quarks and one d quark, a good explanation of static properties, e.g. magnetic moment, can be achieved. However, experimental results of the pion-nucleon sigma term value, strange magnetic moment μ_s, strangeness contribution to nucleon form factor [1], as well as the apparent violations in nucleon-antinucleon annihilation reactions involving the ϕ meson [2] indicate that the proton might contain a substantial strange quark-antiquark ($s\bar{s}$) component. The strangeness sigma term appears to lie somewhere in the range of 2–7% of the nucleon mass [3]. The substantial Okubo-Zwieg-Iizuka (OZI) rule violations in the $N\bar{N}$ annihilation reactions involving the ϕ meson may suggest the presence of an intrinsic $s\bar{s}$ in the nucleon wave function [4], for instance, the presence of a $q^3 s\bar{s}(\bar{q}^3 s\bar{s})$ piece in the $N(\bar{N})$ wave function. With such an assumption, the ϕ meson could be produced in $N\bar{N}$ annihilation reactions via a shakeout or rearrangement of the strange quarks already stored in the nucleon without the violation of the OZI rule. There are other explanations of the OZI rule violation without introducing a strange component in the nucleon such as the resonance interpretation, instanton induced interaction [5], and rescattering [6].

The European Muon Collaboration spin experiment [7] on deep inelastic scattering of longitudinally polarized muons by longitudinally polarized protons revealed for the first time that the polarization of the strange quark sea may contribute a significant negative value to the proton spin σ_s. This experimental result was confirmed by the subsequent deep inelastic double polarization experiments. Reference [8] analyzed all the available data in a systematic way and found $\sigma_s = -0.10 \pm 0.03$. Among a large number of theoretical works, the chiral quark model (CQM) has been successfully applied to explain the spin and flavor structure of the proton [9,10]. With the fluctuation of the proton into a kaon and a hyperon, the negative polarization of the strange quark sea is explained and other theoretical results are derived consistent with the deep inelastic scattering experimental results [9]. The flavor and spin structures of the nucleon as well as other observables are studied in Ref. [10], with both pseudoscalar and vector mesons as well as octet and decuplet baryons included.

However, the configuration of strange quarks in the nucleon is still an open question. The strangeness magnetic moment μ_s can be extrapolated from the strange magnetic form factor $G_M^s(Q^2)$ at the momentum transfer $Q^2 = 0$ measured in the parity violation experiments of electron scattering from a nucleon [11]. Most experimental measurements suggest a positive value for μ_s, in contrast to the recent experiment data [12] and most theoretical calculations which have obtained negative values for this observable [13,14]. A recent work [15] has proposed a different form for the strangeness content of the proton. Instead of

*On leave from Department of Physics, Tomsk State University, 634050 Tomsk, Russia

the 5-quark component, which consists of a uud cluster and a $s\bar{s}$ pair proposed for solving the puzzle of violation of the OZI rule, Ref. [15] treats the strange quark piece in terms of pentaquark configurations. Different pentaquark configurations that may be contained in the proton may yield both positive and negative values for the strangeness spin and magnetic moment of the proton.

The experimental results on μ_s, which is extracted from experimental data on $G_M^s(Q^2)$, are rather uncertain due to the large uncertainties in $G_M^s(Q^2)$ and the extrapolation approach. So it is believed that the proton-antiproton reactions involving ϕ production may be another platform to be applied to tackle the possible configuration of strange quarks in the proton. In the present work we consider the strange content in the proton wave function in three models, namely, the uud cluster with an $s\bar{s}$ sea-quark component, kaon-hyperon clusters based on the chiral quark model, and the pentaquark picture $uuds\bar{s}$. The theoretical σ_s, μ_s, and branching ratios of the reactions $p\bar{p} \to \phi X$ ($X = \pi^0, \eta, \rho^0, \omega$) will be compared to experimental data. We resort to the $^3P_0$ quark model [16] and the nearest threshold dominance model [17] to obtain quantitative predictions for the branching ratios of the annihilation reactions from atomic $p\bar{p}$ states with the relative orbital angular momentum $L = 0$ [18]. The paper is organized as follows. The proton wave functions are briefly described in Sec. II while σ_s and μ_s are calculated and discussed in Sec. III for various strangeness quark configurations. In Sec. IV we evaluate the branching ratios for the reactions $p\bar{p} \to \phi X$ for the three forms of proton wave functions by using the $^3P_0$ quark model. Finally a summary and conclusion are given in Sec. V.

II. PROTON WAVE FUNCTIONS

The proton wave function in the presence of strange quarks may include a 5-quark component $qqqs\bar{s}$ in addition to the uud quark component, taking generically the form

$$|p\rangle = A|uud\rangle + B|uuds\bar{s}\rangle, \tag{1}$$

where A and B are the amplitudes for the 3- and 5-quark components in the proton, respectively [19]. The possible spin-flavor structures of the 5-quark components discussed in the $N\bar{N}$ annihilation process are considered in the next three subsections.

A. Proton wave function with an explicit $s\bar{s}$ sea-quark component

We consider the idea that strange quarks are present in the form of an $s\bar{s}$ sea-quark component in the proton state. This idea was proposed for describing the apparent violation of the OZI rule in the ϕNN production process [20] and in more general form used to discuss the ϕ meson production in $N\bar{N}$ annihilation reactions [4]. The corresponding 5-quark component for this model can be written in Fock space as

$$|uuds\bar{s}\rangle^{s\bar{s}} = a_0|(uud)_{(1/2)}(s\bar{s})_0\rangle_{(1/2)} + a_1|(uud)_{1/2}(s\bar{s})_1\rangle_{(1/2)}, \tag{2}$$

where the subscripts denote the spin coupling of the quark clusters, and a_0 and a_1 represent the amplitudes for the spin 0 and spin 1 components of the admixed $s\bar{s}$ pairs.

B. Proton wave function based on a chiral quark model

In the chiral quark model, the dominant process is the fluctuation of a valence quark q into a quark q' plus a Goldstone boson (GB) which in turn forms a $(q\bar{q}')$ system [21]. After the fluctuation of the u and d quarks in the proton, one of these quarks turns into a quark plus a quark-antiquark pair involving a strange quark. This idea was considered, for example, for calculating the flavor and spin content of the proton [9,10]. To obtain the proton wave function we consider the SU(3) invariant interaction Lagrangian of baryon octet with nonet of pseudoscalar mesons,

$$\mathcal{L}_I = -g_8\sqrt{2}(\alpha[\bar{B}BP]_F + (1-\alpha)[\bar{B}BP]_D) - g_1\frac{1}{\sqrt{3}}[\bar{B}BP]_S, \tag{3}$$

where $g_8 = 3.8$ and $g_1 = 2.0$ are coupling constants [22] and α is known as the $F/(F+D)$ ratio with $F \simeq 0.51$, $D \simeq 0.76$ [23]. The square brackets denote the SU(3) invariant combinations,

$$[\bar{B}BP]_F = \mathrm{Tr}(\bar{B}PB) - \mathrm{Tr}(\bar{B}BP), \tag{4}$$

$$[\bar{B}BM]_D = \mathrm{Tr}(\bar{B}PB) + \mathrm{Tr}(\bar{B}BP) - \frac{2}{3}\mathrm{Tr}(\bar{B}B)\mathrm{Tr}(P), \tag{5}$$

$$[\bar{B}BP]_S = \mathrm{Tr}(\bar{B}B)\mathrm{Tr}(P), \tag{6}$$

where B and P are the baryon octet and pseudoscalar meson nonet matrices, respectively, given by

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}, \tag{7}$$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & \frac{-2\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} \end{pmatrix}. \tag{8}$$

The part of the interaction Lagrangian which allows for a fluctuation of the proton into kaons and hyperons is contained in

$$\mathcal{L}_I = -g_1\bar{p}\eta_1 p + g_8\Big[\bar{p}\pi^0 + \frac{1-4\alpha}{\sqrt{3}}\bar{p}\eta_8 + \frac{1+2\alpha}{\sqrt{3}}\bar{\Lambda}K^- + (2\alpha-1)\bar{\Sigma}^0K^- - \sqrt{2}\bar{n}\pi^- + \sqrt{2}(2\alpha-1)\bar{\Sigma}^-K^0\Big]p + \cdots. \quad (9)$$

The final states resulting from pseudoscalar meson emission by the proton are summarized as

$$|\Psi\rangle \sim -g_1|p\eta_1\rangle + g_8\Big[\frac{1-4\alpha}{\sqrt{3}}|p\eta_8\rangle + |p\pi^0\rangle + \frac{1+2\alpha}{\sqrt{3}}|\Lambda K^+\rangle + (2\alpha-1)|\Sigma^0K^+\rangle - \sqrt{2}|n\pi^+\rangle + \sqrt{2}(2\alpha-1)|\Sigma^+K^0\rangle\Big]. \quad (10)$$

In the absence of the fluctuation, the proton is made up of the conventional two u quarks and one d quark. Thus $\Psi(p)$ may be interpreted as the 5-quark component of the proton wave function which is given by

$$|uuds\bar{s}\rangle^{\rm CQM} = G_1|\Sigma^0K^+\rangle + G_2|\Sigma^+K^0\rangle + G_3|\Lambda^0K^+\rangle + G_4|p\eta_1\rangle + G_5|p\eta_8\rangle, \quad (11)$$

where the G_i are the coefficients corresponding to the respective factor in Eq. (10). Each component in the last equation can be represented in terms of quark cluster configurations as

$$\begin{aligned} |p\eta_{1,8}\rangle &= |(uud)_{(1/2)}(s\bar{s})_0\rangle_{(1/2)},\\ |\Sigma^0K^+\rangle &= |(uds)_{(1/2)}(u\bar{s})_0\rangle_{(1/2)},\\ |\Sigma^+K^0\rangle &= |(uus)_{(1/2)}(d\bar{s})_0\rangle_{(1/2)},\\ |\Lambda^0K^+\rangle &= |(usd)_{(1/2)}(u\bar{s})_0\rangle_{(1/2)}. \end{aligned} \quad (12)$$

C. Proton wave function including general configurations of the *uuds* subsystem

Another, more general form of the 5-quark component was proposed and analyzed in Ref. [15]. Instead of first generating a meson coupling to a baryon cluster, they considered the genuine 5-quark or $q^4\bar{q}$ pentaquark component in the proton. In this model the 5-quark component may be expressed in terms of the $uuds$ and the $\bar{s}$ wave functions as

$$|uuds\bar{s}\rangle^{uuds} = |(uuds)\bar{s}\rangle_{(1/2)}. \quad (13)$$

The flavor wave functions for the $uuds\bar{s}$ components are usually constructed by coupling the $uuds$ to the $\bar{s}$ flavor wave function. The configurations studied in [15] include at most one unit of orbital angular momentum. The favored configurations are connected to a positive sign for the strangeness magnetic moment and a negative one for the strangeness contribution to the proton spin.

III. STRANGENESS MAGNETIC MOMENT AND SPIN OF THE PROTON

In the nonrelativistic quark model the strangeness magnetic moment operator $\vec{\mu}_s$ and the strangeness contribution to the proton spin operator $\vec{\sigma}_s$ are defined as

$$\vec{\mu}_s = \frac{e}{2m_s}\sum_i \hat{S}_i(\hat{\ell}_s + \hat{\sigma}_s), \quad (14)$$

$$\vec{\sigma}_s = \hat{\sigma}_s + \hat{\sigma}_{\bar{s}}. \quad (15)$$

$\hat{S}_i$ is the strangeness counting operator with eigenvalue $+1$ for an s and -1 for an $\bar{s}$ quark and m_s is the constituent mass of the strange quark. To calculate the matrix elements of these operators explicit forms of the spin-flavor wave functions of the proton including orbital angular momentum are needed.

For the first model the spin-flavor wave function can be constructed by coupling the $|s\bar{s}\rangle_{j_s=0,1}$ configuration to the $|uud\rangle_{1/2}$ cluster. Since the admixed $s\bar{s}$ carries negative intrinsic parity, an orbital P-wave ($\ell = 1$) has to be introduced into the nucleon quark cluster wave function. The simplest configuration (see also Ref. [20]) corresponds to a $1S$-state of the $s\bar{s}$ pair moving in a P-wave relative to the (uud) valence quark cluster of the nucleon. Then the 5-quark component with total angular momentum $1/2$ can be written in the general form,

$$|uuds\bar{s}\rangle^{s\bar{s}}_{(1/2),m_{ps\bar{s}}=(1/2)} = \sum_{j_s,j_i=0,1}\alpha_{j_sj_i}|[(s\bar{s})_{j_s}\otimes\ell=1]_{j_i}\otimes(uud)_{(1/2)}\rangle_{(1/2),m_{ps\bar{s}}=(1/2)}, \quad (16)$$

with the normalization $\sum_{j_s,j_i=0,1}|\alpha_{j_sj_i}|^2 = 1$.

Similarly, for the proton wave function in the CQM, where the sea-quark contributions are embedded in the pseudoscalar mesons, a relative P-wave between the pseudoscalars and the uud or hyperon clusters has to be included. The spin-flavor wave function with spin $+1/2$ for each coupled meson-baryon state of Eq. (12) may be expressed as

$$|uuds\bar{s}\rangle^{\rm CQM}_{(1/2),(1/2)} = |[(q\bar{s})_{j_s=0}\otimes\ell=1]_{j_i}\otimes(qqs)_s\rangle_{(1/2),m_{ps\bar{s}}=(1/2)}. \quad (17)$$

Wave functions of the pentaquark $uuds\bar{s}$ states employed in the third model are more complicated because no restrictions are set concerning the subclusters. One has to carefully consider the coupling of the color, spin, flavor, and spatial parts to construct the total wave functions [15]. The color part of the antiquark in the pentaquark states is a [11] antitriplet, denoted by the Weyl tableau of the SU(3) group. Hence the color symmetry of all the $uuds$ configurations is limited to a [211] triplet in order to form a pentaquark color singlet labeled by the Weyl tableau [222]. Three flavor symmetry patterns exist for the $uuds$ system corresponding to the octet representation for the proton: $[31]_F$, $[22]_F$, and $[211]_F$ characterized by the S_4 Young tableau. However, the pentaquark should be antisymmetric under any permutation of the 4-quark configuration. If the spatial wave function is symmetric, the spin-flavor part of the $uuds$ component must be a [31] state in order to form the antisymmetric color-spin-flavor $uuds$ part of the pentaquark wave function. For instance, the flavor symmetry representations $[31]_F$ and $[211]_F$ may combine with the spin symmetry state $[22]_S$ to form the mixed symmetry spin-flavor states $[31]_{FS}$ (the explicit forms may be found in [15,24,25]). In this work we consider only the case that the $uuds$ component is in the ground state with the spin symmetry $[22]_S$ corresponding to spin 0, and the relative orbital angular momentum between the $uuds$ component and the $\bar{s}$ is of one unit to obtain the positive parity for the proton wave function.

Theoretical results for the strangeness magnetic moment μ_s of the proton and the strangeness contribution to the proton spin σ_s are listed in Table I. In the first model we have fixed the configuration parameters as $\alpha_{1,0} = \alpha_{1,1} = \bar{\alpha}$. The strangeness magnetic moment μ_s depends explicitly on $\alpha_{0,1}$, which is related to the amplitude for the $s\bar{s}$ quark cluster with spin 0. Setting $\alpha_{0,1} = 0$ is equivalent to excluding the quantum number $J^{PC} = 0^{-+}$ for the $s\bar{s}$ admixture in the nucleon wave function connected to the production of η and η' in $N\bar{N}$ annihilation as discussed in [19,26]. The chiral quark model always gives results for μ_s and σ_s, which are negative, and the size of the strangeness contribution depends on the coupling g_8^2. For the third model, we show only the results for the cases where the $uuds$ component is in the ground state with the spin-flavor configurations $[31]_{FS}[211]_F[22]_S$ and $[31]_{FS}[31]_F[22]_S$ and the relative motion between the $uuds$ component and the $\bar{s}$ is a P-wave.

All the three models yield negative values for the strangeness contribution to the proton spin, which is consistent with present experimental results [7,8]. Negative values for the strangeness magnetic moment also result from all three models. Note that we restricted the considerations of Ref. [15] to the pentaquark components with the $uuds$ configurations $[31]_{FS}[211]_F[22]_S$ and $[31]_{FS}[31]_F[22]_S$, respectively.

TABLE I. Strangeness magnetic moment and spin of the proton for the three models of the 5-quark component.

$\vert uuds\bar{s}\rangle$	$\mu_s(\frac{eB^2}{2m_s})$	$\sigma_s(B^2)$
$s\bar{s}$	$-0.55\bar{\alpha}\alpha_{0,1}$	$-1.22\bar{\alpha}^2$[18]
CQM	$-1.1g_8^2$	$-0.31g_8^2$
$[31]_{FS}[211]_F[22]_S$	$-\frac{1}{3}$[15]	$-\frac{1}{3}$[15]
$[31]_{FS}[31]_F[22]_S$	$-\frac{1}{3}$[15]	$-\frac{1}{3}$[15]

IV. $N\bar{N}$ TRANSITION AMPLITUDE AND BRANCHING RATIOS

To describe the annihilation reactions $N\bar{N} \to X\phi$ ($X = \pi^0$, η, ρ^0, ω) we use an effective transition dynamics, which is evaluated in the context of a simple constituent quark model. In this specific process the ϕ meson couples to the intrinsic $s\bar{s}$ component of the nucleon, which is the leading order OZI allowed contribution. The process $p\bar{p}$ annihilation into ϕX involving the 5-quark components in the proton wave function can be described by the quark line diagrams of Fig. 1. In the hadronic transition the effective quark annihilation operator is taken with the quantum numbers of the vacuum ($^3P_0$, isospin $I = 0$ and color singlet). Meson decays and $N\bar{N}$ annihilation into two mesons are well described phenomenologically using such an effective quark-antiquark vertex. At least for meson decay, this approximation has been given a rigorous basis in strong-coupling QCD. The nonperturbative $q\bar{q}\ ^3P_0$ vertex is defined according to [27]

$$V^{ij} = \sum_\mu \sigma_{-\mu}^{ij} Y_{1\mu}(\vec{q}_i - \vec{q}_j)\delta^{(3)}(\vec{q}_i + \vec{q}_j)(-1)^{1+\mu} 1_F^{ij} 1_C^{ij}, \tag{18}$$

where $Y_{1\mu}(\vec{q}) = |\vec{q}|\mathcal{Y}_{1\mu}(\hat{q})$ with $\mathcal{Y}_{1\mu}(\hat{q})$ being the spherical harmonics in momentum space, and 1_F^{ij} and 1_C^{ij} are unit

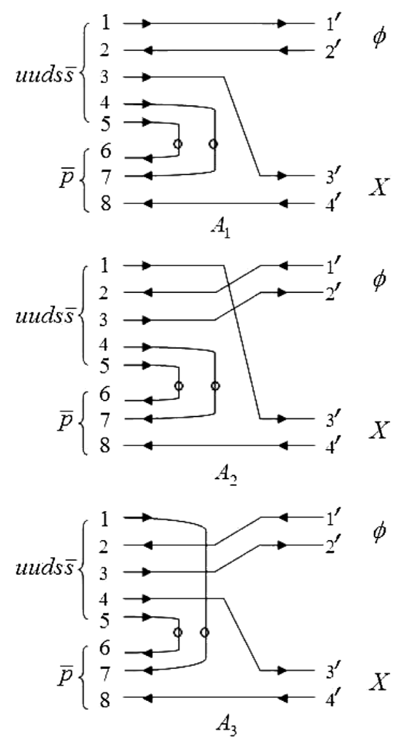

FIG. 1. Quark line diagrams for the production of two-meson final states in $p\bar{p}$ annihilation. Small circles refer to the effective vertex of the $^3P_0$ quark dynamics for $q\bar{q}$ annihilation. The first diagram corresponds to the shakeout of the intrinsic $s\bar{s}$ component of the proton wave function [4,18].

operators in flavor and color spaces, respectively. The spin operator $\sigma^{ij}_{-\mu}$ is part of the $^3P_0$ vertex, destroying or creating quark-antiquark pairs with spin 1.

In the momentum space representation the transition amplitudes for the quark diagrams of Fig. 1 are given by

$$T_{A_l} = \int d^3q_1 \ldots d^3q_8 d^3q_{1'} \ldots d^3q_{4'} \langle \phi X | \vec{q}_{1'} \ldots \vec{q}_{4'} \rangle \times \langle \vec{q}_{1'} \ldots \vec{q}_{4'} | \mathcal{O}_{A_l} | \vec{q}_1 \ldots \vec{q}_8 \rangle \langle \vec{q}_1 \ldots \vec{q}_8 | (uuds\bar{s}) \otimes (\bar{u}\,\bar{u}\,\bar{d}) \rangle \tag{19}$$

where $(\bar{u}\,\bar{u}\,\bar{d})$ stands for the antiproton wave function and $(uuds\bar{s})$ for the 5-quark component of the proton wave function. The effective operators $\mathcal{O}_{A_l}$ take the form

$$\mathcal{O}_{A_1} = \lambda_{A_1} \delta^{(3)}(\vec{q}_1 - \vec{q}_{1'}) \delta^{(3)}(\vec{q}_2 - \vec{q}_{2'}) \times \delta^{(3)}(\vec{q}_3 - \vec{q}_{3'}) \delta^{(3)}(\vec{q}_8 - \vec{q}_{4'}) V^{56} V^{47}, \tag{20}$$

$$\mathcal{O}_{A_2} = \lambda_{A_2} \delta^{(3)}(\vec{q}_2 - \vec{q}_{1'}) \delta^{(3)}(\vec{q}_3 - \vec{q}_{2'}) \times \delta^{(3)}(\vec{q}_1 - \vec{q}_{3'}) \delta^{(3)}(\vec{q}_8 - \vec{q}_{4'}) V^{56} V^{47}, \tag{21}$$

$$\mathcal{O}_{A_3} = \lambda_{A_3} \delta^{(3)}(\vec{q}_2 - \vec{q}_{1'}) \delta^{(3)}(\vec{q}_3 - \vec{q}_{2'}) \times \delta^{(3)}(\vec{q}_4 - \vec{q}_{3'}) \delta^{(3)}(\vec{q}_8 - \vec{q}_{4'}) V^{56} V^{17}. \tag{22}$$

The δ-functions represent the noninteracting and continuous quark-antiquark lines in the diagrams. The constants λ_{A_l} describe the effective strength of the transition topology and are considered to be overall fitting parameters in the phenomenological description of experimental data. Since the 5-quark component is treated as a small perturbative admixture in the proton ($B^2 \ll 1$), we ignore the transition amplitude with the term $\langle \vec{q}_1 \ldots \vec{q}_8 | (uuds\bar{s}) \otimes (\bar{u}\,\bar{u}\,\bar{d}\,\bar{s}\,s) \rangle$ or the rearrangement process [4].

In this work the internal spatial wave functions are taken in the harmonic oscillator approximation. For the mesons M (ϕ and X), the wave function can be expressed in terms of the quark momenta as

$$\langle M | \vec{q}_{i'} \vec{q}_{j'} \rangle \equiv \varphi_M(\vec{q}_{i'}, \vec{q}_{j'}) \chi_M = N_M \exp\left\{ -\frac{R_M^2}{8} (\vec{q}_{i'} - \vec{q}_{j'})^2 \right\} \chi_M, \tag{23}$$

with $N_M = (R_M^2/\pi)^{3/4}$ and R_M is the meson radial parameter. The spin-color-flavor wave function is denoted by χ_M. The baryon wave functions are given by

$$\langle B | \vec{q}_i \vec{q}_j \vec{q}_k \rangle \equiv \varphi_B \chi_B = N_B \exp\left\{ -\frac{R_B^2}{4} \left[(\vec{q}_j - \vec{q}_k)^2 + \frac{(\vec{q}_j + \vec{q}_k - 2\vec{q}_i)^2}{3} \right] \right\} \chi_B, \tag{24}$$

where $N_B = (3R_B^2/\pi)^{3/2}$ and R_B is the baryon radial parameter. For the first and the second model the full 5-quark component wave function, resulting from the coupling of a meson to a baryon, is given by

$$\langle \vec{q}_1 \ldots \vec{q}_5 | uuds\bar{s} \rangle = \varphi_{uuds\bar{s}}(\vec{q}_1, \ldots, \vec{q}_5) \chi_{uuds\bar{s}} = N_{uuds\bar{s}} \exp\left\{ -\frac{R_B^2}{4} \left[(\vec{q}_4 - \vec{q}_5)^2 + \frac{(\vec{q}_4 + \vec{q}_5 - 2\vec{q}_3)^2}{3} \right] \right\} \exp\left\{ -\frac{R^2}{8} (\vec{q}_3 + \vec{q}_4 + \vec{q}_5 - \vec{q}_1 - \vec{q}_2)^2 \right\} \times Y_{1\mu}(\vec{q}_3 + \vec{q}_4 + \vec{q}_5 - \vec{q}_1 - \vec{q}_2) \exp\left\{ -\frac{R_M^2}{8} (\vec{q}_1 - \vec{q}_2)^2 \right\} (\chi_B \otimes \chi_M). \tag{25}$$

The exponential form with the radial parameter R and the spherical harmonics $Y_{1\mu}$ together represent the internal relative P-wave between the 3-quark and 2-quark clusters.

For the third model the proton wave function includes a pentaquark component $uuds\bar{s}$ with the $uuds$ part in the ground state and the P-wave internal relative orbital angular momentum between $uuds$ and the $\bar{s}$. One may write the spatial wave function of the pentaquark component $uuds\bar{s}$ as

$$\varphi_{uuds\bar{s}}(\vec{q}_1, \ldots, \vec{q}_5) = N_{uuds\bar{s}} \exp\left\{ -\frac{R_B^2}{4} \left[(\vec{q}_2 - \vec{q}_3)^2 + \frac{(\vec{q}_2 + \vec{q}_3 - 2\vec{q}_4)^2}{3} + \frac{(\vec{q}_2 + \vec{q}_3 + \vec{q}_4 - 3\vec{q}_5)^2}{6} + \frac{(\vec{q}_2 + \vec{q}_3 + \vec{q}_4 + \vec{q}_5 - 4\vec{q}_1)^2}{10} \right] \right\} Y_{1\mu}\left(\frac{\vec{q}_2 + \vec{q}_3 + \vec{q}_4 + \vec{q}_5 - 4\vec{q}_1}{\sqrt{20}} \right). \tag{26}$$

By choosing the plane wave basis for the relative motion of the proton and antiproton, the initial-state wave functions in the center of momentum system ($\vec{k} = \vec{q}_1 + \vec{q}_2 + \vec{q}_3 + \vec{q}_4 + \vec{q}_5$) are obtained as

$$\langle \vec{q}_1 \ldots \vec{q}_8 | (uuds\bar{s}) \otimes (\bar{u}\,\bar{u}\,\bar{d}) \rangle = \varphi_{uuds\bar{s},\bar{p}} [\chi_{uuds\bar{s}} \otimes \chi_{\bar{p}}]_{S,S_z}, \tag{27}$$

with

$$\varphi_{uuds\bar{s},\bar{p}} = \varphi_{uuds\bar{s}}\varphi_{\bar{p}}\delta^{(3)}(\vec{q}_1 + \vec{q}_2 + \vec{q}_3 + \vec{q}_4 + \vec{q}_5 - \vec{k}) \times \delta^{(3)}(\vec{q}_6 + \vec{q}_7 + \vec{q}_8 + \vec{k}). \quad (28)$$

The spins of the $p\bar{p}$ system are coupled to the total spin S with projection S_z. Similarly, the final state ϕX wave functions in the center of momentum system are given by ($\vec{q} = \vec{q}_{1'} + \vec{q}_{2'}$)

$$\langle \phi X | \vec{q}_{1'} \dots \vec{q}_{4'} \rangle = \varphi_{\phi,X}[\chi_\phi \otimes \chi_X]_{j_i,m_\epsilon}, \quad (29)$$

with

$$\varphi_{\phi,X} = \varphi_\phi \varphi_X \delta^{(3)}(\vec{q} - \vec{q}_{1'} - \vec{q}_{2'})\delta^{(3)}(\vec{q} + \vec{q}_{3'} + \vec{q}_{4'}). \quad (30)$$

The spins of the two-meson states are coupled to j_i with projection m_ϵ.

In the low-momentum approximation, the transition amplitude T_{fi} of the annihilation reaction of the S-wave $\bar{p}p$ initial state i to the P-wave two-meson final state f with the quark line diagrams A_I as shown in Fig. 1 is derived as

$$T_{fi}(\vec{q}, \vec{k}) = \lambda_{A_I} F_{L=0,\ell_f=1} q \exp\{-Q_q^2 q^2 - Q_k^2 k^2\}\langle f|O_{A_I}|i\rangle. \quad (31)$$

The index i represents the initial state ${}^{2I+1,2S+1}L_J$, where L is the orbital angular momentum, S is the total spin, J is the total angular momentum, and I is the total isospin. The final state f is represented by the set of quantum numbers $f = \{\ell_f jJ'\}$, where ℓ_f is the relative orbital angular momentum. The constants $F_{0,1}$, Q_q^2, and Q_k^2 are geometrical constants depending on the radial parameters. The matrix element $\langle f|O_{A_I}|i\rangle$ is the spin-flavor weight for a quark line diagram A_I. The detailed evaluation of the expression in Eq. (31) is given in the Appendix.

As we consider $p\bar{p}$ annihilations at rest where the strong interaction between the proton and antiproton may largely distort the $\bar{p}p$ hydrogenlike wave function at small distances [28], the effect of the initial-state interaction is in general not negligible. The inclusion of the initial-state interaction for the atomic state of the $p\bar{p}$ system results in the transition amplitude [29],

$$T_{f,LSJ}(\vec{q}) = \int d^3k T_{fi}(\vec{q}, \vec{k})\phi^I_{LSJ}(\vec{k}), \quad (32)$$

where $\phi^I_{LSJ}(\vec{k})$ is the protonium wave function in momentum space for fixed isospin I. The partial decay width for the transition of the $p\bar{p}$ state to the two-meson state ϕX is given by

$$\Gamma_{p\bar{p}\to\phi X} = \frac{1}{2E}\int \frac{d^3p_\phi}{2E_\phi}\frac{d^3p_X}{2E_X}\delta^{(3)}(\vec{p}_\phi + \vec{p}_X) \times \delta(E - E_\phi - E_X)|T_{f,LSJ}(\vec{q})|^2, \quad (33)$$

where E is the total energy ($E = 1.876$ GeV) and $E_{\phi,X} = \sqrt{m^2_{\phi,X} + \vec{p}^2_{\phi,X}}$ is the energy of outgoing meson ϕ and X with mass $m_{\phi,X}$ and momentum $\vec{p}_{\phi,X}$. With the explicit form of the transition amplitude given by Eq. (31), the partial decay width for the S to P transition ($L = 0$, $\ell_f = 1$) is written as

$$\Gamma_{p\bar{p}\to\phi X} = \lambda^2_{A_I} f(\phi, X)\langle f|O_{A_I}|i\rangle^2 \gamma(I, J), \quad (34)$$

with

$$\gamma(I, J) = |F_{0,1}\int d^3k\phi^I_{LSJ}(\vec{k})\exp\{-Q_k^2 k^2\}|^2 \quad (35)$$

and the kinematical phase-space factor defined by

$$f(\phi, X) = \frac{q^3}{8E^2}\exp\{-2Q_q^2 q^2\}. \quad (36)$$

The spin-flavor weights $\langle f|O_{A_I}|i\rangle$ for the transitions $N\bar{N} \to \phi X$ involving the different 5-quark components of the proton wave functions are listed in Table II. For the initial values of the total angular momentum J the statistical weights $1/4$ and $3/4$ have to be added for $J = 0$ and $J = 1$, respectively. Finally the branching ratio of S-wave $p\bar{p}$ annihilation to the final state ϕX is then given by

$$\mathrm{BR}(\phi, X) = \frac{(2J + 1)\Gamma_{p\bar{p}\to\phi X}}{4\Gamma_{\mathrm{tot}}(J)}, \quad (37)$$

where $\Gamma_{\mathrm{tot}}(J)$ is the total annihilation width of the $p\bar{p}$ atomic state with fixed principal quantum number [30].

The model dependence in Eq. (34) may be reduced by choosing a simplified phenomenological approach that has been applied in studies of two-meson branching ratios in nucleon-antinucleon [29] and radiative protonium annihilation [31]. Namely, the phase space factor of Eq. (36) is obtained in the harmonic oscillator approximation for the hadron wave function, depending on the relative momentum q and the masses of ϕX system. Instead we use a kinematical phase-space factor of the phenomenological form

TABLE II. Spin-flavor matrix elements $\langle f|O_{A_I}|i\rangle$ for the transitions $p\bar{p}(L = 0) \to \phi X(\ell_f = 1)$ which are described by the quark line diagram A_I. Here η_{ud} refers to the nonstrange flavor combination $\eta_{ud} = (u\bar{u} + d\bar{d})/\sqrt{2}$.

Transition	$s\bar{s}_{A_1}$	CQM	$[31][31][22]_{A_1}$	$[31][211][22]_{A_1}$
${}^{11}S_0 \to \omega\phi$	$\frac{5}{9\sqrt{6}}$	−0.097	$\frac{5}{36\sqrt{6}}$	$\frac{5}{36\sqrt{6}}$
${}^{33}S_1 \to \pi^0\phi$	$\frac{5}{27\sqrt{2}}$	0.031	$\frac{5}{108\sqrt{2}}$	$\frac{5}{108\sqrt{2}}$
${}^{31}S_0 \to \rho^0\phi$	$\frac{13}{27\sqrt{6}}$	0.040	$\frac{13}{108\sqrt{6}}$	$\frac{13}{108\sqrt{6}}$
${}^{13}S_1 \to \eta_{ud}\phi$	$\frac{1}{9\sqrt{2}}$	0.013	$\frac{1}{36\sqrt{2}}$	$\frac{1}{36\sqrt{2}}$

TABLE III. Branching ratio BR($\times 10^4$) for the transition $p\bar{p} \to \phi X$ ($X = \pi^0$, η, ρ^0, ω) in $p\bar{p}$ annihilation at rest. The results indicated by $\star$ are normalized to the experimental values.

Transition	BR^{exp}	$BR^{s\bar{s}}$	BR^{CQM}	$BR^{[31][31][22]}$	$BR^{[31][211][22]}$
${}^{11}S_0 \to \omega\phi$	6.3 ± 2.3	6.3$\star$	6.3$\star$	6.3$\star$	6.3$\star$
${}^{33}S_1 \to \pi^0\phi$	5.5 ± 0.7	5.4	1.6	5.4	5.4
${}^{31}S_0 \to \rho^0\phi$	3.4 ± 1.0	3.8	0.87	3.8	3.8
${}^{13}S_1 \to \eta\phi$	0.9 ± 0.3	1.4–1.8	0.20–0.27	1.4–1.8	1.4–1.8

$$f(\phi, X) = q \cdot \exp\{-a_s(s - s_{\phi X})^{1/2}\}, \tag{38}$$

where $s_{\phi X} = (m_\phi + m_X)^{1/2}$ and $\sqrt{s} = (m_\phi^2 + q^2)^{1/2} + (m_X^2 + q^2)^{1/2}$. The constant $a_s = 1.2\ \text{GeV}^{-1}$ is obtained from a phenomenological fit to the momentum dependence of various multipion final states in $p\bar{p}$ annihilation [17]. In addition, the functions $\gamma(I, J)$, depending on the initial-state interaction, are related to the probability for a protonium state to have isospin I and spin J with the normalization condition $\gamma(0, J) + \gamma(1, J) = 1$. Here we adopt for a protonium state the probability $\gamma(I, J)$ and the total decay width $\Gamma_{tot}(J)$ obtained in an optical potential calculation [32], where explicit values are listed in [30].

In Table III we give the theoretical results for the branching ratios of Eq. (37) compared with experimental data. The branching ratios $BR^{s\bar{s}}$, resulting from the first model where the proton wave function has an explicit $s\bar{s}$ admixture, have already been derived and studied in Ref. [18] by using the same approach. Annihilation processes in the first and third model are described by the quark line diagram A_1. Since the effective strength parameter λ_{A_1} is *a priori* unknown, it has to be adjusted to data. For this purpose one entry in the table (as indicated by $\star$) is normalized to the observed value.

For the second chiral model where the proton wave function contains a kaon-hyperon or eta-proton cluster component, all three quark line diagrams may have contributions to the $\bar{p}p$ annihilation process. However, the process proceeding by the diagram A_1 with the $|p\eta\rangle$ component in the proton wave function has no contribution to the transition because of orthogonality to the ϕ state. Therefore, the annihilation process in the second model can only be described by the quark line diagrams A_2 and A_3. Considering the same annihilation pattern in these two diagrams, for simplicity the two unknown strength parameters are of the same order with $\lambda_{A_2} = \lambda_{A_3}$. Model predictions are also normalized to experimental data (as indicated by $\star$). For final states with $X = \eta$, the physical η meson is produced by its nonstrange component η_{ud} with $\eta = \eta_{ud}(\sqrt{1/3}\cos\theta - \sqrt{2/3}\sin\theta)$ corresponding to a variation of the pseudoscalar mixing angle θ from $\theta = -10.7^o$ to $\theta = -20^o$.

As shown in Table III, the theoretical results of the first and third models, where the proton wave function possesses, respectively, a small kaon-hyperon component and a pentaquark, are in good agreement with the experimental data. Note that for these two cases the annihilation processes $p\bar{p} \to \phi X$ are described with the quark line diagram A_1.

Please note that in the present model we cannot give a reliable estimate for the genuine transition strength of the $p\bar{p}$ annihilation processes. Therefore, the measured production rates cannot be used to get an estimate for the $s\bar{s}$ content in the nucleon or for the coefficient B in Eq. (1).

V. SUMMARY

Three models have been studied for the proton involving intrinsic strangeness in the form of a 5-quark component $qqqs\bar{s}$ in the wave function. In particular, the proton wave function is made up of a uud configuration and a uud cluster with an $s\bar{s}$ sea-quark component, kaon-hyperon clusters based on the simple chiral quark model, or a pentaquark component $uuds\bar{s}$. We have calculated the strangeness magnetic moment μ_s and spin σ_s for the first and second models and generated negative values in line with recent experimental indication. Similarly, for the third model we pick these configurations, where negative values for μ_s and σ_s result [15].

We further applied quark line diagrams supplemented by the ${}^3P_0$ vertex to study the annihilation reactions $p\bar{p} \to \phi X$ ($X = \pi^0$, η, ρ^0, ω) with the three types of proton wave functions. Excellent agreements of the model predictions in the first and third models with the experimental data are found for the branching ratios of the reactions of the $L = 0$ atomic $p\bar{p}$ state to ϕX ($X = \pi^0$, η, ρ^0, ω).

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APPENDIX A: TRANSITION AMPLITUDES OF THE ANNIHILATION PROCESSES $p\bar{p} \to \phi X$

To describe the annihilation process $p\bar{p} \to \phi X$, where $X = \pi^0, \eta, \rho^0, \omega$ with the proton wave function with $s\bar{s}$ sea quark, we consider the shakeout of the intrinsic $s\bar{s}$ component of the proton wave function as indicated in the diagram A_1. With the operator $\mathcal{O}_{A_1}$ and the full account of the spin-flavor-color-orbital structure of the initial and final states, the transition amplitude can be written as

$$T_{if}^{s\bar{s}} = \lambda_{A_1}\left\langle f \left| \sum_{\nu,\lambda} (-1)^{\nu+\lambda} \sigma_{-\nu}^{56} \sigma_{-\lambda}^{47} 1_F^{56} 1_F^{47} 1_C^{56} 1_C^{47} I_{\text{spatial}}^{s\bar{s}} \right| i \right\rangle, \tag{A1}$$

where

$$|i\rangle = |\{\chi_{(1/2),m_{ps\bar{s}}}(uuds\bar{s}) \otimes \chi_{(1/2),m_{\bar{p}}}(\bar{u}\bar{u}\bar{d})\}_{S,S_z} \otimes (L,M)\rangle_{J,J_z}, \tag{A2}$$

$$|f\rangle = |\{\chi_{1,m_\alpha}(\phi) \otimes \chi_{j_m,m_{3',4'}}(X)\}_{j,m_\epsilon} \otimes (\ell_f, m_f)\rangle_{J,J_z}. \tag{A3}$$

The spin-flavor-color content of the clusters is denoted by $\chi \equiv \chi_\sigma \otimes \chi_F \otimes \chi_C$. The 5-quark component $\chi_{(1/2),m_{ps\bar{s}}}(uuds\bar{s})$ is defined as

$$\chi_{(1/2),m_{ps\bar{s}}}(uuds\bar{s}) = |\{\chi_{j_s,m_s}(s\bar{s}) \otimes (\ell = 1, \mu)\}_{j_i,m_i} \otimes \chi_{(1/2),m_p}(uud)\rangle_{(1/2),m_{ps\bar{s}}}. \tag{A4}$$

The spatial amplitude $I_{\text{spatial}}^{s\bar{s}}$ is explicitly given by

$$I_{\text{spatial}}^{s\bar{s}} = \int d^3q_1 \ldots d^3q_8 d^3q_{1'} \ldots d^3q_{4'} \varphi_{\phi,X} \mathcal{O}_{A_1}^{\text{spatial}} \varphi_{uuds\bar{s},\bar{p}}, \tag{A5}$$

where

$$\begin{aligned}\mathcal{O}_{A_1}^{\text{spatial}} &= Y_{1\lambda}(\vec{q}_4 - \vec{q}_7)\delta^{(3)}(\vec{q}_4 + \vec{q}_7)Y_{1\nu}(\vec{q}_5 - \vec{q}_6) \\ &\times \delta^{(3)}(\vec{q}_5 + \vec{q}_6)\delta^{(3)}(\vec{q}_1 - \vec{q}_{1'})\delta^{(3)}(\vec{q}_2 - \vec{q}_{2'}) \\ &\times \delta^{(3)}(\vec{q}_3 - \vec{q}_{3'})\delta^{(3)}(\vec{q}_8 - \vec{q}_{4'}).\end{aligned} \tag{A6}$$

Partial wave amplitudes can be obtained by projecting the transition amplitude onto the partial waves, where $L = 0$ and $l_f = 1$ corresponds to $\bar{p}p$ annihilation at rest. In the low-momentum approximation the integrals can be done analytically, and the partial wave amplitude in the leading order of the external momenta q is given by

$$I_{\text{spatial},L=0,l_f=1}^{s\bar{s}} = qF_{0,1}^{s\bar{s}} f_{0,1}^{s\bar{s}}(\nu, \lambda, \mu, m_f)\exp\{-Q_q^2 q^2 - Q_k^2 k^2\}. \tag{A7}$$

The geometrical constant $F_{0,1}^{s\bar{s}}$ and the spin-angular momentum function $f_{0,1}^{s\bar{s}}(\nu, \lambda, \mu, m_f)$ are given by

$$\begin{aligned}F_{0,1}^{s\bar{s}} &= 2N\pi^2\left(\frac{1}{Q_{p_2}^2}\right)^{3/2}\left(\frac{3\sqrt{\pi}}{(Q_{p_4}^2)^{5/2}} - \frac{3\sqrt{\pi}}{4(Q_{p_3}^2)^{5/2}}\right), \\ f_{0,1}^{s\bar{s}}(\nu, \lambda, \mu, m_f) &= (-1)^\nu \delta_{\nu,-\lambda}\delta_{\mu,m_f},\end{aligned} \tag{A8}$$

where $N = N_\phi N_X N_{uuds\bar{s}} N_{\bar{p}}$, and the coefficients in the exponential expression depend on the meson and baryon size parameters,

$$\begin{aligned}Q_k^2 &= \frac{4R_M^2R_B^2 + 9R^2R_B^2 + 3R_M^2R^2}{24(R_M^2 + 3R_B^2)}, \\ Q_q^2 &= \frac{12R_B^4 + 5R_M^2R_B^2 + 36R^2R_B^2 + 12R_M^2R^2}{24(R_M^2 + 3R_B^2)}, \\ Q_{p_2}^2 &= R_M^2, \qquad Q_{p_3}^2 = \frac{1}{2}(R_M^2 + 3R_B^2), \qquad Q_{p_4}^2 = 2R_B^2.\end{aligned} \tag{A9}$$

By using the spatial wave amplitude $I_{\text{spatial}}^{s\bar{s}}$ we obtain the transition amplitude $T_{if}^{s\bar{s}}$ taking the form as in Eq. (31) with the spin-color-flavor weight,

$$\langle f|O_{A_1}|i\rangle = \left\langle f \left| \sum_{\nu,\lambda} (-1)^{\nu+\lambda}\sigma_{-\nu}^{56}\sigma_{-\lambda}^{47} 1_F^{56} 1_F^{47} 1_C^{56} 1_C^{47} (-1)^\nu \times \delta_{\nu,-\lambda}\delta_{\mu,m_f} \right| i \right\rangle. \tag{A10}$$

According to the $^3P_0$ quark model the matrix element $\langle f|O_{A_1}|i\rangle$ can be evaluated by using the two-body matrix elements for spin, flavor, and color given by

$$\langle 0|\sigma_\nu^{ij}|\chi_{m_{ij}}^{J_{ij}}(ij)\rangle = \delta_{J_{ij},1}\delta_{m_{ij},-\nu}(-1)^\nu\sqrt{2}, \tag{A11}$$

$$\langle 0|1_F^{ij}|\chi_{t_{ij}}^{T_{ij}}(ij)\rangle = \delta_{T_{ij},0}\delta_{t_{ij},0}\sqrt{2}, \tag{A12}$$

and

$$\langle 0|1_C^{ij}|q_\alpha^i \bar{q}_\beta^j\rangle = \delta_{\alpha\beta}, \tag{A13}$$

where α and β are the color indices. The spin-color-flavor weights $\langle f|O_{A_1}|i\rangle$ are evaluated for various transitions, as listed in Table II.

In case of the simple chiral quark model, the annihilation processes are described by the quark line diagrams A_2 and A_3. Then the transition amplitude is set up as

$$T_{if}^{\text{CQM}} = T_{if}^{\text{CQM}}(\mathcal{O}_{A_2}) + T_{if}^{\text{CQM}}(\mathcal{O}_{A_3}), \tag{A14}$$

where the corresponding transition amplitudes for the two quark line diagrams are given by

$$T_{if}^{\rm CQM}(\mathcal{O}_{A_2}) = \lambda_{A_2}\left\langle f \left| \sum_{\nu,\lambda}(-1)^{\nu+\lambda}\sigma_{-\nu}^{56}\sigma_{-\lambda}^{47}1_F^{56}1_F^{47}1_C^{56}1_C^{47} \times I_{{\rm spatial},A_2}^{\rm CQM} \right| i\right\rangle \quad (A15)$$

and

$$T_{if}^{\rm CQM}(\mathcal{O}_{A_3}) = \lambda_{A_3}\left\langle f \left| \sum_{\nu,\lambda}(-1)^{\nu+\lambda}\sigma_{-\nu}^{56}\sigma_{-\lambda}^{17}1_F^{56}1_F^{17}1_C^{56}1_C^{17} \times I_{{\rm spatial},A_3}^{\rm CQM} \right| i\right\rangle. \quad (A16)$$

The initial state $|i\rangle$ and the final state $|f\rangle$ take the same form as defined in Eq. (A2) and (A3), but the 5-quark component in this case is given by

$$\chi_{(1/2),m_{KY}}(uuds\bar{s}) = \sum_{i=1}^{3} G_i|\{\chi^i_{j_s,m_s}(q\bar{s}) \otimes (\ell = 1, \mu)\}_{j_i,m_i} \otimes \chi^i_{(1/2),m_Y}(qqs)\rangle_{(1/2),m_{KY}}, \quad (A17)$$

where $i = 1, 2, 3$ represent the kaon-hyperon clusters $K^+\Sigma^0$, $K^0\Sigma^+$ and $K^+\Lambda^0$, respectively, and the coefficients G_i are as defined in Eq. (11).

In the low-momentum approximation the partial wave amplitude from each of the quark line diagrams $A1$ and $A2$ in leading order of the external momentum q takes the general form as in Eq. (A7) but with different coefficients. In order to combine the two transition amplitudes, we choose the radial parameters for the baryons and mesons as $R_B = 3.1$ GeV^{-1}, $R_M = 4.1$ GeV^{-1} [18] and the size parameter between the two quark clusters as $R = 4.1$ GeV^{-1}. Then the total transition amplitude Eq. (A14) becomes

$$T_{if}^{\rm CQM} = \lambda_{\rm CQM}F_{0,1}^{\rm CQM} q \exp\{-Z_q^2q^2 - Z_k^2k^2\}\langle f|O_{\rm CQM}|i\rangle, \quad (A18)$$

where $F_{0,1}^{\rm CQM} = 4.9 \times 10^{-4}$ GeV^{-11}, $Z_q \simeq 2.3$ GeV^{-1} and $Z_k \simeq 1.3$ GeV^{-1}, and $\lambda_{A_2} = \lambda_{A_3} = \lambda_{\rm CQM}$. The total spin-color-flavor weight $\langle f|O_{\rm CQM}|i\rangle$ is calculated with the spin-angular momentum wave functions in Eq. (A17) and its elements are derived as

$$f_{0,1}^{\rm CQM} = -(-1)^\nu\delta_{\nu,-\lambda}\delta_{\mu,m_f} + 2(-1)^\mu\delta_{\mu,-\nu}\delta_{\lambda,m_f} + 2(-1)^\lambda\delta_{\mu,-\lambda}\delta_{\nu,m_f}. \quad (A19)$$

Finally, we discuss the third model where the proton wave function includes a 5-quark component in the form of a pentaquark configuration. The ϕ production is described by only the quark line diagram A_1, and the transition amplitude takes the same form as Eq. (A1) but the 5-quark component $|uuds\bar{s}\rangle$ is given by

$$\chi_{(1/2),m_{ps\bar{s}}}(uuds\bar{s}) = |\{\chi_{(1/2),m_{\bar{s}}}(\bar{s}) \otimes (\ell = 1, \mu)\}_{j_i,m_i} \otimes \chi_{s,s_z}(uuds)\rangle_{(1/2),m_{ps\bar{s}}}. \quad (A20)$$

In the low-momentum approximation, the partial wave amplitude and for the transition of the S-wave $\bar{p}p$ state to the P-wave two-meson final states takes the same form as Eq. (A7). The spin-angular momentum function $f_{0,1}^{s\bar{s}}(\nu, \lambda, \mu, m_f)$ is also the same as the one in Eq. (A8) but the corresponding geometrical constant is given by

$$F_{0,1} = -\frac{3}{16}\sqrt{5}N\pi^4\left(\frac{1}{Q_{p_2}^2}\right)^{3/2}\left(\frac{(\frac{1}{Q_{p_4}^2})^{3/2}}{(Q_{p_3}^2)^{5/2}} - \frac{4(\frac{1}{Q_{p_3}^2})^{3/2}}{(Q_{p_4}^2)^{5/2}}\right), \quad (A21)$$

with the constants depending on the baryon and meson size parameters,

$$Q_k^2 = \frac{7R_B^2}{30} - \frac{R_B^4}{2(3R_B^2 + R_M^2)}, \quad Q_q^2 = \frac{1}{8}R_B^2\left(5 - \frac{R_B^2}{3R_B^2 + R_M^2}\right),$$
$$Q_{p_2}^2 = R_B^2 + \frac{R_M^2}{2}, \quad Q_{p_3}^2 = \frac{1}{2}(3R_B^2 + R_M^2), \quad Q_{p_4}^2 = 2R_B^2. \quad (A22)$$

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