Polarization phenomena for processes $\bar{p}+p\to P+V$ and mechanisms of OZI violations in φ production

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The spin structure of the matrix element for $p\bar{p}$ annihilation in flight in the process $\bar{p}+p\to P+V$ with $P=\pi^0,\eta,\eta'$, and $V=\rho^0,\omega,\varphi$, is constructed for collinear kinematics. The expressions for all the one-spin and two-spin polarization observables are found, and the consequences for the triplet enhancement hypothesis of strange particle production in $p\bar{p}$ collisions are discussed.

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I. INTRODUCTION

Results from polarized deep inelastic scattering experiments [1–5] indicate that the contribution ΔS from strange quarks and antiquarks to the spin of the proton, for momentum transfer square $Q^2\geqslant 3\ \mathrm{GeV}^2$, is quite large: $\Delta S=-0.11\pm 0.03$. This negative sign explains also the results [6] of the measurement of the Λ polarization in the target fragmentation region in neutrino induced reactions for incident momenta larger than 5 GeV/c [7], where the Λ hyperons have been found to be polarized longitudinally with a value $P_\Lambda=-0.56\pm 0.13$, the sign being negative with respect to the momentum transfer direction.

The existence of an $s\bar{s}$ component of a nonperturbative nature in the nucleon, even at relatively small momentum transfer [8], would have important consequences on the Okubo-Zweig-Iizuka (OZI) rule [9–11]. Large violations of this rule have been recently reported in $\bar{p}p$ annihilation into vector mesons, at rest [12–15]. It has been shown that the anomalous yields of φ mesons, produced in the reactions $\bar{p}+p\to\varphi+\pi^0$ and $\bar{p}+p\to\varphi+\gamma$ are related to the S-wave nature of the annihilation channel, however, with no large deviations from the naive OZI predictions in the P-wave annihilation channel. In the $\bar{p}+p\to\varphi+\pi$ reaction, selection rules in C and P parities permit only a spin triplet $\bar{p}p$ initial state, leading to the suggestion [8] that the φ production, induced by polarized nucleon-antinucleon could be related to ΔS. Note that the large violation of OZI-rule in $\bar{p}+p\to\varphi+\pi^0$ (at threshold) is in favor of the positive contribution of the $s\bar{s}$ polarized sea [16]. This finding is not in contradiction with the presence of a negative $s\bar{s}$-polarized component at high momentum transfer (small distances). This means that the strange quark contribution ΔS can be Q^2 dependent, changing sign at $Q^2\simeq 1\ \mathrm{GeV}^2$.

It must be pointed out that majority of the experimental evidence of the sign of ΔS have been obtained at rather high momentum transfers. In the nonperturbative region there is little information about ΔS. That is, there is only one experimental result [17] on neutrino and antineutrino scattering, indicating that the nucleon strange axial form factor, which is directly related to ΔS, could be slightly positive with a large error bar, for $0.5\ \mathrm{GeV}^2\leqslant Q^2\leqslant 1\ \mathrm{GeV}^2$.

An alternative explanation for the large OZI violation found in $\bar{p}p$ annihilation at rest, is that it is not connected at all to the $s\bar{s}$ component of nucleon. It has been suggested recently [18–20] that triangular rescattering diagrams with KK^* and $\rho\rho$ in the intermediate state, and interference effects between different amplitudes may also explain the very large violation of the OZI rule, observed in $\bar{p}+p\to\varphi+\pi^0$, in the absence of any $s\bar{s}$ component in the nucleon. In any case, the $s\bar{s}$ recipe [8] relates the enhancement of φ-production with definite polarization properties of initial $\bar{p}p$ and pp states in φ-producing processes.

Interesting properties of η-meson production in NN collision processes such as [21–26] $p+p\to p+p+\eta$, $n+p\to n+p+\eta$, $n+p\to d+\eta$, can be exploited also in the framework of hypothesis of $s\bar{s}$-nonperturbative component of nucleon, although the η meson does not contain only $s\bar{s}$ quarks, as is the case for the φ meson. As in the case of φ-producing reactions, one can interpret η-production enhancement in pp collisions in terms of a large $s\bar{s}$ component in the nucleon, with one major difference. In vector meson production, it has been shown that the triplet state of pp (or $\bar{p}p$) is most suitable for transferring the $s\bar{s}$ component from the initial nucleon (antinucleon) to the final vector meson. In the case of pseudoscalar η production, it is the *singlet* state which is favored for transferring $s\bar{s}$ component to the final η meson, thus explaining the large value of singlet amplitude in comparison with the triplet [27] ones.

Therefore, to test the hypothesis about polarized strangeness of nucleon, different polarization experiments will be very interesting. To obtain theoretical predictions for such experiments which are more sensitive to this special dynamics, some preliminary (kinematical) analysis of the polarization phenomena must be done. The point is that sometimes the polarization effects can be predicted without any specific dynamical assumptions, but only using the symmetry properties of fundamental interactions, such as P and C invariances, Pauli principle and isotopic symmetry of the strong interaction, as was previously demonstrated for the processes of vector meson production in nucleon-nucleon collisions $N+N\to N+N+V^0$ [16], $N+N\to d+V$ [28], near threshold.

In this work we study the polarization phenomena for $\bar{p}+p\to P+V$. Our main aim is to construct the spin structure of the scattering matrix element in general form, with subse-

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quent study of polarization effects. We discuss the case of collinear meson production where $\theta=0,\pi$ [θ being the P-meson production angle in the c.m. system (c.m.s.)]. Obvious advantages of this special kinematical regime are that the cross section is maximal at these production angles (thus, more convenient for experimental testing of the predictions), and the spin structure of the scattering matrix element is very simple. Indeed, as we will discuss in detail in Sec. II, because of the conservation of the total helicity in the collinear regime, we have two independent spin structures for $p\bar{p}$ annihilation in flight, instead of six we would have had for arbitrary θ. In order to appreciate the significance of this simplification, let us recall that even in the special kinematical regime (the so-called orthogonal kinematics, where the V-meson production angle in the c.m.s. is $\pi/2$), one has three independent spin structures, and thus three independent amplitudes to worry about [29]. In addition to the simplification of the spin structures, the polarization phenomena are also simplified in the collinear regime. For example, some polarization observables such as vector analyzing powers, as well as the polarizations of the final particles are identically zero in any model. Furthermore, the amplitudes in the collinear regime are functions of a single kinematical variable only, namely the total energy. The collinear kinematics is very attractive for testing the C invariance of the strong interactions also. As it is possible to discriminate between the kinematical and dynamical properties of the polarization observables in the collinear regime, it can be considered as one of the most suitable regimes for testing the hypothesis of triplet enhancement for the strange particle production in NN and $\bar{N}N$ collisions.

Our paper is organized as follows. In Sec. II we parametrize the collinear amplitude for $\bar{p}+p\to P+V$ in terms of two possible spin structures, corresponding to singlet and triplet $\bar{p}p$ interactions, and analyze one-spin and two-spin polarization observables in terms of these singlet and triplet amplitudes. We also discuss the implications of triplet enhancement for the polarization phenomena in φ production.

II. POLARIZATION PHENOMENA IN COLLINEAR KINEMATICS

The general formalism for analyzing the polarization phenomena is developed in Ref. [30] for arbitrary θ except $\theta=0,\pi$. Thus, in the collinear regime one cannot start with this general formalism, and extrapolate the results to $\theta=0,\pi$. Instead, one needs to develop an independent formalism from the scratch, and that is what will be done next.

The general spin structure of amplitude of any process $\bar{p}+p\to P+V$ for the collinear kinematics can be parametrized in the following form:

$$\mathcal{M}=\tilde{\chi}_2\sigma_2[ig_0(s)\vec{k}\cdot\vec{\epsilon}^{\,*}+g_1(s)\vec{\sigma}\cdot\vec{\epsilon}^{\,*}\times\vec{k}]\chi_1, \qquad (1)$$

where χ_1 and χ_2 are the two-component spinors of initial proton and antiproton, respectively, $\vec{\epsilon}$ is the polarization three-vector of produced V meson, $\vec{k}$ is unit vector along three-momentum of colliding particles; $g_0(s)$ and $g_1(s)$ are the complex singlet and triplet amplitudes, which are functions of a single invariant variable s (square of the total energy of colliding particles).

Obviously, the amplitudes g_0 and g_1 are different for $\theta=0$ and $\theta=\pi$ in the general case. But for the processes $\bar{p}+p\to P^0+V^0$ (that is, production of both mesons with definite C parities), C-invariance of strong interaction predicts the following relations between these amplitudes at $\theta=0$ and $\theta=\pi$:

$$g_0(s,\theta=0)=-g_0(s,\theta=\pi), \qquad g_1(s,\theta=0)=g_1(s,\theta=\pi). \qquad (2)$$

One can see from Eq. (2) that for the annihilation of stopped antiprotons (in the S state, where any θ dependence of amplitudes must disappear), the following expressions are obtained for the threshold values of these amplitudes:

$$g_0(s=4m^2)=0, \quad g_1(s=4m^2)\neq 0,$$

where m is the nucleon mass. That is, only the triplet annihilation is allowed, and thus the vector mesons must be produced with transversal polarization only. This is an interesting example of correlation between polarization phenomena and internal symmetry properties (namely, C invariance) of fundamental interactions. In principle, this connection can be used as a new basis for testing the C invariance of the strong interactions, using the polarization phenomena.

Using the parametrizaton (1) of the collinear amplitude, one can establish the dependence of the differential cross section on the polarizations $\vec{P}_1$ and $\vec{P}_2$ of the colliding particles, taking the P invariance of the strong interactions into account:

$$\frac{d\sigma}{d\Omega}(\vec{P}_1,\vec{P}_2)=\frac{1}{4}\sigma_s(1-\vec{P}_1\cdot\vec{P}_2)+\frac{1}{2}\sigma_t[1+(\vec{k}\cdot\vec{P}_1)(\vec{k}\cdot\vec{P}_2)], \qquad (3)$$

where σ_s and σ_t are the cross-sections of $\bar{p}p$-annihilation from the singlet and triplet states, respectively (triplet state is characterized here by a unit value of the projection of total spin of $\bar{p}p$ system).

We used in Eq. (3) the following expressions for the polarization projectors in terms of $\vec{P}_1$ and $\vec{P}_2$ for description of two fermion system in singlet and triplet states:

$$P_s=\frac{1}{4}(1-\vec{P}_1\cdot\vec{P}_2), \quad P_t=\frac{1}{2}[1+(\vec{k}\cdot\vec{P}_1)(\vec{k}\cdot\vec{P}_2)]. \qquad (4)$$

Using the general form for the differential cross section for the collision of two polarized fermions in the collinear regime

$$\frac{d\sigma}{d\Omega}(\vec{P}_1,\vec{P}_2)=\left(\frac{d\sigma}{d\Omega}\right)_0[1+\mathcal{A}_1(\vec{P}_1\cdot\vec{P}_2)+\mathcal{A}_2(\vec{k}\cdot\vec{P}_1)(\vec{k}\cdot\vec{P}_2)], \qquad (5)$$

one can obtain the following expressions for the spin correlation coefficients $\mathcal{A}_1$ and $\mathcal{A}_2$, in terms of the collinear amplitudes g_0 and g_1:

$$\mathcal{A}_1=\frac{-\sigma_s}{\sigma_s+2\sigma_t}=\frac{-|g_0|^2}{|g_0|^2+2|g_1|^2},$$
$$\mathcal{A}_2=\frac{2\sigma_t}{\sigma_s+2\sigma_t}=\frac{2|g_1|^2}{|g_0|^2+2|g_1|^2}. \quad (6)$$

One can see from Eq. (6) that

$$\mathcal{A}_1\leqslant 0,\quad \mathcal{A}_2\geqslant 0,\quad -\mathcal{A}_1+\mathcal{A}_2=1, \quad (7)$$

which are valid for any values of the amplitudes g_0 and g_1. The relation (7) between $\mathcal{A}_1$ and $\mathcal{A}_2$ is a result of the absence of the annihilation from the triplet state of $\bar{p}p$ system with $\lambda=0$, where λ is defined as the projection of the total spin of $\bar{p}p$ system along the direction of initial $\bar{p}$.

One can see that coefficients $\mathcal{A}_1$ or $\mathcal{A}_2$ characterize the relative role of the singlet and triplet annihilation for the reactions $\bar{p}+p\to P+V$ in collinear kinematics. So, by measuring the differential cross-section, $(d\sigma/d\Omega)_0\approx|g_0|^2+2|g_1|^2$, with unpolarized particles in initial and final states, as well as the coefficient $\mathcal{A}_1$ one can determine the moduli of the complex amplitudes g_0 and g_1.

The same information can also be obtained from the study of the polarized V production with unpolarized $p\bar{p}$. Indeed, even for the collision of unpolarized particles, V meson must have nonzero tensor polarization. To show this, let us consider the most general form of density matrix for the V meson produced in collinear regime:

$$\rho_{ab}=k_ak_b+\rho\left(k_ak_b-\frac{1}{3}\delta_{ab}\right), \quad (8)$$

where the real function $\rho=\rho(s)$, is given as

$$\rho=-\frac{3|g_1|^2}{|g_0|^2+2|g_1|^2}. \quad (9)$$

So the nonzero elements of density matrix ρ_{ab} are determined by the following expressions (in Cartesian coordinates with the z axis chosen along $\vec{k}$):

$$\rho_{xx}=\rho_{yy}=-\frac{1}{3}\rho=\frac{1}{2}\mathcal{A}_2,\quad \rho_{zz}=1+\frac{2}{3}\rho. \quad (10)$$

Equations (7) and (10) enable us to suggest a simpler strategy for determining $|g_0|$ and $|g_1|$ through the measurement of $(d\sigma/d\omega)_0$ and ρ. One can also see from the same equations that by measuring only ρ_{xx} (or ρ_{zz}), we can predict the values of both coefficients $\mathcal{A}_1$ and $\mathcal{A}_2$. This can be used, in principle, for the polarimetry of high energy $\bar{p}$ beam in the process $\vec{\bar{p}}+\vec{p}\to P+V$, if target polarization is known.

The elements of the V-meson density matrix can be determined by studying the angular dependence of V-meson decay products. For example, for the transition probability of the decay $V\to P+P$ (for instance $\varphi\to K+\bar{K},\rho\to\pi+\pi$), this dependence is characterized by ρ:

$$W(\psi)\approx 1+a\cos^2\psi,\quad a=-3\left(1+\frac{1}{\rho}\right), \quad (11)$$

where ψ is the angle between the three-momentum of V-meson in the c.m.s. of $\bar{p}+p\to P+V$, and the three-momentum of the secondary P meson produced in the next step decay of V in its rest frame (that is in $V\to P+P$).

In this connection, we would like to also note that the other possible one-spin polarization observables, namely the analyzing powers of $\vec{\bar{p}}+p\to P+V$ and $\bar{p}+\vec{p}\to P+V$, vanish in the collinear regime, as can be proven easily on the basis of general symmetry considerations, independently of the values of the amplitudes g_0 and g_1.

All these polarization observables are T-even, and are determined by the moduli of g_0 and g_1. But the relative phase of these amplitudes can be determined using correlation polarization experiments, such as the measurement of dependence of polarization properties of produced V mesons on the polarization of one of the initial particles. The general parametrization of density matrix of V mesons, produced in $\bar{p}+\vec{p}\to P+V$, can be written in the following form:

$$\rho_{ab}(P)=i\epsilon_{abc}P_c\rho_1+i\epsilon_{abc}k_c(\vec{k}\cdot\vec{P})\rho_2+[k_a(\vec{k}\times\vec{P})_b+k_b(\vec{k}\times\vec{P})_a]\rho_3, \quad (12)$$

where $\vec{P}$ is the target polarization.

The real functions $\rho_1(s)$ and $\rho_2(s)$, which determine the T-even vector polarization of V meson in the process $\bar{p}+\vec{p}\to P+V$, cannot be measured using the most probable decays of V mesons, such as $V\to P+P$, $V\to P+\gamma$, $V\to l^+ + l^-$, $V\to P+l^+ + l^-$, etc., which are induced by the strong or electromagnetic interactions (with P-parity conservation). But, all such decays are very suitable for measuring the tensor polarization of V mesons, i.e., the symmetrical part of the density matrix. So, the quantity ρ_3, which characterizes the T-odd correlation of polarizations of initial proton and the produced V meson, can be measured.

The coefficients ρ_i can be expressed in terms of the amplitudes g_0 and g_1 as follows:

$$\rho_1\left(\frac{d\sigma}{d\Omega}\right)_0=\frac{\mathrm{Re}(g_0g_1^*)}{|g_0|^2+2|g_1|^2},$$
$$\rho_2\left(\frac{d\sigma}{d\Omega}\right)_0=\frac{|g_1|^2-\mathrm{Re}(g_0g_1^*)}{|g_0|^2+2|g_1|^2}, \quad (13)$$
$$\rho_3\left(\frac{d\sigma}{d\Omega}\right)_0=\frac{-\mathrm{Im}(g_0g_1^*)}{|g_0|^2+2|g_1|^2}.$$

We see from Eq. (13) that, the quantity ρ_3 is the most sensitive polarization observable to the relative phase between the collinear amplitudes. All these results are model independent, following only from the general symmetry properties of strong interactions.

Let us finally analyze the consequences of the special dynamical assumption, namely, the enhancement [8] of triplet production of φ-mesons in $\overline{p}+p\to\varphi+\pi$ process. In the case of annihilation of stopped antiprotons (annihilation in the *S*-state), this hypothesis cannot be tested effectively; because selection rules in *C* and *P* parities allow here annihilation from the triplet state of colliding $\overline{p}+p$, only. But in the case of annihilation in flight this hypothesis can be tested qualitatively. Indeed, in the case of the collinear kinematics this hypothesis implies that the singlet amplitude must be smaller than the triplet one, i.e., $|g_0|\ll|g_1|$, which, in turn yields

$$\mathcal{A}_1=0,\quad \mathcal{A}_2=1,\quad \rho=-\frac{3}{2}, \tag{14}$$

which can be tested experimentally. For example, the angular distribution of decay products from $V\to P+P$ must be as $\sin^2\psi$, which is typical for production of transversally polarized *V* mesons.

III. CONCLUSIONS

We found above the spin structure of the matrix element for the processes $\overline{p}+p\to P+V$ for collinear kinematics, where *P*-meson production angle is equal to 0 or π, in c.m.s. In this special regime, the spin structure of matrix element is described by two scalar amplitudes, namely, the triplet and the singlet ones. We have proposed a two-step realization of complete experiment with the determination of moduli of all amplitudes at the first step, and the relative phase of these amplitudes at the second step. It is important to note that the complete experiment can be realized using only one- and two-spin polarization observables. In any case, the polarization effects in $\overline{p}+p\to P^0+V^0$ will offer opportunities to test qualitatively the hypothesis of the dominance of strange particle production from the triplet states of nucleon-nucleon and nucleon-antinucleon collisions.

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