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Manifestations of hidden polarized strangeness of the nucleon in polarization phenomena for the process $p + \bar{p} \rightarrow P^0 + V^0$

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Abstract. The sensitivities of the one-spin and two-spin polarization observables for $p+\bar{p} \rightarrow P^0+V^0$, with $P^0 = \pi^0, \eta, \eta'$ and $V^0 = \rho, \omega, \phi$, based on the triplet enhancement hypothesis for strangeness production in $p\bar{p}$ collisions are analyzed. The analysis is carried out under special kinematical conditions where the P^0 meson production angle in the CMS is equal to $\pi/2$, for which C- invariance of strong interactions reduces the number of independent amplitudes to three.

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1 Introduction

ϕ meson production in processes $p + \bar{p} \rightarrow \phi + \pi^0$ and $p + \bar{p} \rightarrow \phi + \gamma$ [1-4] with proton-antiproton annihilation in S-state, demonstrates large violation of the OZI rule [5-7] for which various explanations have been suggested [8-11]. The P and C conservation laws allow a spin triplet initial state for process $p + \bar{p} \rightarrow \phi + \pi^0$, that leads to the suggestion [8], that the properties of the ϕ - producing nucleon and anti-nucleon reactions could be related to the value ΔS, which characterizes the strangeness part of the longitudinal proton polarization. The polarized Deep Inelastic Scattering (DIS) experiments [12-16] indicate that this contribution to the proton spin at large momentum transfer square $Q^2 \geq 3GeV^2$ are of the order of $\Delta S = -0.11 \pm 0.03$. The negative sign of this strange contribution is confirmed by the results of [17] based on the measurement of the Λ-polarization (in the target fragmentation region) in neutrino induced reactions for incident momenta larger than 5 Gev/c. In the non-perturbative region there is little information about ΔS. Namely, there is only one experimental result on neutrino and antineutrino scattering by nucleons which indicates that the nucleon strange axial form factor, which is directly related to ΔS, could be slightly positive for $0.5 \leq Q^2 \leq 1GeV^2$.

In the framework of the hypothesis, that there is a sizeable $s\bar{s}$ component of nucleon, it is possible to show that the large violations of the OZI-rule in $p\bar{p}$ annihilation at rest is in favour of a positive contribution of the $s\bar{s}$ polarized sea [19]. This does not contradict the results of polarized DIS, if one assumes that ΔS changes sign in the region of $Q^2 \approx 1GeV^2$. This behaviour of ΔS with Q^2 can be related also to the Q^2 dependence of Drell Hearn-Gerasimov sum rule, which is presently under intensive experimental scrutiny [20].

To test the hypothesis of polarized strangeness of nucleon, different polarization experiments are needed, and to make predictions for such experiments more sensitive to this special dynamics, some preliminary general analysis of polarization phenomena is to be carried out. The point is that sometimes polarization effects can be predicted without any dynamical assumptions, by using only the symmetry properties of fundamental interactions, such as P-invariance, Pauli principle, isotopic spin invariance and C-invariance [21].

We discuss here the polarization phenomena for processes $p + \bar{p} \rightarrow P^0 + V^0$ where P^0 is a pseudoscalar meson (π^0, η, η') and V^0 is a neutral vector meson (ρ^0, ω, ϕ). Our main goal is to analyze the spin structure of the corresponding amplitudes in the general form with a consequent study of the polarization effects. We choose the case of so-called orthogonal kinematics, where the P-meson production angle is $\theta = \pi/2$ in the CMS. In this case, C-invariance of strong interactions decreases the number of independent amplitudes, and thus simplifies the analysis of polarization effects. Therefore, such kinematical conditions are very suitable for testing the hypothesis of triplet enhancement of ϕ-meson production in $p\bar{p}$ collisions.

Our paper is organized as follows: In Sect. 2 we parametrize the spin structure of the matrix element for $p + \bar{p} \rightarrow P^0 + V^0$ processes in terms of the transversal amplitudes, and analyze all possible one-spin and two-spin polarization observables. In Sec.3 we discuss the predictions of the triplet enhancement hypothesis for these polarization observables.

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2 Polarization effects in orthogonal kinematics

In the general case the spin structure of the matrix element of any process $N+\bar{N}\to P+V$ is described by six independent contributions, which can be parametrized as follows (in the CMS):

$$\begin{aligned}\mathcal{M}(\bar{N}N\to PV)&=\tilde{\chi}_2\sigma_2F\chi_1,\\ F&=\mathbf{n}\cdot\mathbf{U}^*(\sigma\cdot\mathbf{m}f_1+\sigma\cdot\mathbf{k}f_2)\\ &\quad+\mathbf{m}\cdot\mathbf{U}^*f_3+\mathbf{k}\cdot\mathbf{U}^*f_4\\ &\quad+\sigma\cdot\mathbf{n}(\mathbf{m}\cdot\mathbf{U}^*f_5+\mathbf{k}\cdot\mathbf{U}^*f_6),\end{aligned}\tag{1}$$

where χ_1 and χ_2 are the two-component spinors of N and $\bar{N}$, $\mathbf{U}$ is the 3-vector of V-meson polarization, $\mathbf{k}$ is a unit vector along the 3-momentum of colliding particles, $\mathbf{n}=\mathbf{k}\times\mathbf{q}/|\mathbf{k}\times\mathbf{q}|$, $\mathbf{m}=\mathbf{n}\times\mathbf{k}$, and $\mathbf{q}$ is the 3-momentum of P-meson. The complex amplitudes f_i depend on two invariant variables s and t.

Therefore, the complete experiment is very complicated, involving 11 independent polarization measurements (including differential cross-section with unpolarized particles, 6 moduli of amplitudes $f_i, i=1\ldots6$, and 5 relative phases for any values of variables s and t).

But for processes $\bar{p}+p\to P^0+V^0$, namely the production of mesons with definite values of C-parity, C-invariance of strong interactions imply the following symmetry properties for amplitudes $f_i(s,cos\theta)$, under the transformation $cos\theta\to -cos\theta$:

$$\begin{aligned}f_i(s,-cos\theta)&=-f_i(s,cos\theta),\text{for } i=1,3,5\\ f_i(s,-cos\theta)&=+f_i(s,cos\theta),\text{for } i=2,4,6\end{aligned}\tag{2}$$

Therefore polarization observables for $\bar{p}+p\to P^0+V^0$ must also have definite symmetry properties relative to $\theta=\pi/2$. This is one example of the relation between the internal symmetry properties of fundamental interactions (C-invariance in this case) and the polarization phenomena. Therefore, testing the symmetry properties of polarization observables in $\bar{p}+p\to P^0+V^0$ can be considered as a new possible method of checking the C-invariance of strong interactions.

One can conclude from the symmetry relations (2), that at $\theta=\pi/2$ only 3 amplitudes are allowed. So the analysis of polarization effects under such kinematical conditions must be simpler than in the general case.

To optimize the procedure of complete experiment we shall choose instead of (1) another, but equivalent, representation of the amplitude at $\theta=\pi/2$, namely:

$$\begin{aligned}F(\theta=\pi/2)\equiv F_t&=h_1\mathbf{k}\cdot\mathbf{U}^*\frac{1+\sigma\cdot\mathbf{n}}{\sqrt{2}}+h_2\mathbf{k}\cdot\mathbf{U}^*\frac{1-\sigma\cdot\mathbf{n}}{\sqrt{2}}\\ &\quad+h_3(\mathbf{n}\cdot\mathbf{U}^*)(\sigma\cdot\mathbf{k})\end{aligned}\tag{3}$$

The advantage of this parametrization is that the simplest polarization observables for $\bar{p}+p\to P^0+V^0$ are determined by the moduli squares of the amplitudes only. For example, the differential cross-section with unpolarized particles is given by the simple expression:

$$\left(\frac{d\Gamma}{d\Omega}\right)_0=|h_1|^2+|h_2|^2+|h_3|^2\tag{4}$$

The analyzing powers (A_p and $A_{\bar{p}}$, for polarized target and polarized beam respectively) can be written as:

$$A_p\left(\frac{d\Gamma}{d\Omega}\right)_0=A_{\bar{p}}\left(\frac{d\Gamma}{d\Omega}\right)_0=|h_1|^2-|h_2|^2\tag{5}$$

Polarization properties of V-mesons, produced in the collision of unpolarized particles, can in general be described by following density matrix:

$$\begin{aligned}\rho_{ab}&=\rho_1m_am_b+\rho_2n_an_b+\rho_3k_ak_b\\ &\quad+\rho_4(m_ak_b+m_bk_a)+i\rho_5(m_ak_b-m_bk_a),\\ \rho_1&+\rho_2+\rho_3=1,\end{aligned}\tag{6}$$

where we used the P-invariance of the strong interactions. In the framework of orthogonal kinematics, one can show that $\rho_1=\rho_4=\rho_5=0$. In this case the non zero elements of ρ_i are given in terms of the amplitudes h_i as:

$$\begin{aligned}\rho_2&=\frac{|h_3|^2}{|h_1|^2+|h_2|^2+|h_3|^2},\\ \rho_3&=\frac{|h_1|^2+|h_2|^2}{|h_1|^2+|h_2|^2+|h_3|^2}.\end{aligned}\tag{7}$$

So, the first step of the complete experiment, under such kinematical conditions, can include only the one-spin polarization observables, namely, the analyzing power A_p (or $A_{\bar{p}}$) and the element ρ_2 (or ρ_3) of the V-meson density matrix, in addition to the differential cross-section with unpolarized particles, $(d\Gamma/d\Omega)_0$.

For the determination of relative phases of the amplitudes h_i (at $\theta=\pi/2$), correlation polarization experiments are necessary. The dependence of the differential cross-section on the polarizations $\mathbf{P}_1$ and $\mathbf{P}_2$ of the colliding particles can be written in the following general structure (taking into account of the P-invariance of strong interactions):

$$\begin{aligned}\frac{d\Gamma}{d\Omega}(\mathbf{P}_1,\mathbf{P}_2)&=\left(\frac{d\Gamma}{d\Omega}\right)_0(1+\mathcal{A}_{mm}\mathbf{m}\cdot\mathbf{P}_1\mathbf{m}\cdot\mathbf{P}_2\\ &\quad+\mathcal{A}_{nn}\mathbf{n}\cdot\mathbf{P}_1\mathbf{n}\cdot\mathbf{P}_2\\ &\quad+\mathcal{A}_{kk}\mathbf{k}\cdot\mathbf{P}_1\mathbf{k}\cdot\mathbf{P}_2+\mathcal{A}_{mk}\mathbf{m}\cdot\mathbf{P}_1\mathbf{k}\cdot\mathbf{P}_2\\ &\quad+\mathcal{A}_{km}\mathbf{k}\cdot\mathbf{P}_1\mathbf{m}\cdot\mathbf{P}_2)\end{aligned}\tag{8}$$

where $\mathcal{A}_{ab}$ are the spin correlation coefficients for $\overline{\mathbf{p}}+\mathbf{p}\to P+V$, which are determined by the following combinations of amplitudes h_i:

$$\begin{aligned}\mathcal{A}_{mm}&=-\frac{2\,\mathrm{Re}\,(h_1h_2^*)+|h_3|^2}{|h_1|^2+|h_2|^2+|h_3|^2},\\ \mathcal{A}_{nn}&=-\frac{|h_1|^2+|h_2|^2-|h_3|^2}{|h_1|^2+|h_2|^2+|h_3|^2}\\ \mathcal{A}_{kk}&=-\frac{2\,\mathrm{Re}\,(h_1h_2^*)-|h_3|^2}{|h_1|^2+|h_2|^2+|h_3|^2},\\ \mathcal{A}_{mk}=\mathcal{A}_{km}&=\frac{2\,\mathrm{Im}\,(h_1h_2^*)}{|h_1|^2+|h_2|^2+|h_3|^2}\end{aligned}\tag{9}$$

One can show that $1=\mathcal{A}_{kk}-\mathcal{A}_{mm}-\mathcal{A}_{nn}$, independently of the values of the amplitudes. The coefficients

$\mathcal{A}_{mk}$ and $\mathcal{A}_{km}$, as well as a particular combination of the coefficients $\mathcal{A}_{ab}$, namely:

$$\mathcal{A}_{mm} + \mathcal{A}_{kk} = -\frac{4\,\mathrm{Re}\,(h_1 h_2^*)}{|h_1|^2 + |h_2|^2 + |h_3|^2}, \tag{10}$$

are sensitive to the relative phases of the amplitudes h_1 and h_2.

To find the other possible phase, it is necessary to measure the dependence of vector-meson polarization on the polarization of the proton target.Denoting the hidden polarized strangeness of the proton target by the pseudovector $\mathbf{P}$, we can write the following general expression for the density matrix:

$$\begin{aligned}\rho_{ab}(P) = \mathbf{m}.\mathbf{P}(&p_1\{m,n\}_{ab} + p_2\{k,n\}_{ab} + ip_3[m,n]_{ab} \\ &+ ip_4[k,n]_{ab}) \\ + \mathbf{n}.\mathbf{P}(&p_5 m_a m_b + p_6 n_a n_b + p_7 k_a k_b \\ &+ p_8\{m,k\}_{ab} + ip_9[m,k]_{ab}) \\ + \mathbf{k}.\mathbf{P}(&p_{10}\{m,n\}_{ab} + p_{11}\{k,n\}_{ab} \\ &+ ip_{12}[m,n]_{ab} + ip_{13}[k,n]_{ab}),\end{aligned} \tag{11}$$

where

$$\{m,n\}_{ab} = m_a n_b + m_b n_a, \quad [m,n]_{ab} = m_a n_b - m_b n_a. \tag{12}$$

The p_i and p_{ij} can be shown to satisfy the following relations:

$$\begin{aligned} p_1 &= p_3 = 0, \\ p_2 D &= \frac{1}{\sqrt{2}}\,\mathrm{Re}\,[(h_1 - h_2)h_3^*], \\ p_4 D &= -\frac{1}{\sqrt{2}}\,\mathrm{Im}\,[(h_1 - h_2)h_3^*], \\ p_5 &= p_6 = p_8 = p_9 = p_{10} = p_{12} = 0, \\ p_{11} D &= \frac{1}{\sqrt{2}}\,\mathrm{Im}\,[(h_1 + h_2)h_3^*], \\ p_{13} D &= \frac{1}{\sqrt{2}}\,\mathrm{Re}\,[(h_1 + h_2)h_3^*], \\ D &= |h_1|^2 + |h_2|^2 + |h_3|^2. \end{aligned} \tag{13}$$

In the light of (13) one can see that, such polarization observables offer sufficient possibilities for measuring the relative phases of all the three complex amplitudes.

Note that the most probable decays of V-mesons, like $V \to P + P$, $V \to P + \gamma$, $V \to l^+ + l^-$ induced by strong and electromagnetic interactions, can not be used for measuring the antisymmetric part of the density matrix $\rho_{ab}(P)$. This general statement follows from the P-invariance of strong and electromagnetic interactions. But in any case it is unnecessary to consider more complicated (i.e. triple) spin correlations to have a complete experiment for the processes $\bar{p} + p \to P^0 + V^0$ at $\theta = \pi/2$.

3 Polarized strangeness of nucleon

Let us analyze here the consequences of the triplet enhancement assumption for the ϕ meson production in $\bar{p} + p \to \phi + \pi$. In the case of annihilation of the stopped antiprotons (which are in the S-state), we can not test this hypothesis, as this process is necessarly in the triplet state, due to C- and P-parity conservation. But in the case of annihilation in flight, the hypothesis can be tested quantitatively.

For example, at $\theta = \pi/2$ we have one singlet and two triplet amplitudes. To forbid the singlet annihilation, we should have the following relation between the h_i amplitudes:

$$h_1(s) + h_2(s) = 0 \tag{14}$$

First of all, this given zero value for the analyzing prowers in $\bar{\mathbf{p}} + p \to P^0 + V^0$ and $\bar{p} + \mathbf{p} \to P^0 + V^0$ processes: $A_p = A_{\bar{p}} = 0$.

The polarization properties of the V-mesons, produced in collisions of unpolarized particles, are characterized by a single parameter ρ_3,

$$\rho_3 = \frac{2|h_1|^2}{2|h_1|^2 + |h_3|^2}. \tag{15}$$

For the spin correlation coefficients $\mathcal{A}_{ab}$ the following expressions are valid:

$$\begin{aligned} \mathcal{A}_{kk} = 1,\ \mathcal{A}_{mk} &= \mathcal{A}_{km} = 0, \\ \mathcal{A}_{mm} = -\mathcal{A}_{nn} &= \frac{2|h_1|^2 - |h_3|^2}{2|h_1|^2 + |h_3|^2} = -1 + 2\rho_3, \end{aligned} \tag{16}$$

i.e., all these polarization observables are determined by the single parameter, $|h_1|^2/|h_3|^2$.

Some special predictions about polarization effects in ϕ-production can be obtained in the framework of the nucleon model in [8], where a nonperturbative $s\bar{s}$ component is assigned to the nucleon. In this model the $s\bar{s}$-pair, in the spin triplet state, must have a unit value of orbital angular momentum relative to the “basic” uud-component of the proton.

To obtain the correct value 1/2 for the proton spin, the total angular momentum of $s\bar{s}$ (i.e. the vector sum of total spin of $s\bar{s}$ and its unit orbital angular momentum) must have two values, namely 0 and 1. Therefore, we can write the following representation for the physical nucleon $|N>$, defined as a definite superposition of $s\bar{s}$, and uud components, with positive P-parity and with total angular momentum 1/2:

$$|N> = (a\mathbf{q}\cdot\mathbf{S} + ib\sigma\cdot\mathbf{q}\times\mathbf{S})|0>, \tag{17}$$

where $\mathbf{S}$ is a vector, describing the polarization properties of the triplet $s\bar{s}$ -system, $\mathbf{q}$ is a unit vector along the 3-momentum of the $s\bar{s}$, relative to the “bare” nucleon, and $|0> = |uud>$. Linearity of (17) with respect to $\mathbf{q}$ is a result of the unit orbital angular momentum of the $s\bar{s}$ component. The quantities $|a|^2$ and $|b|^2$ can be interpreted as the probabilities of both possible values of total angular momentum of the $s\bar{s}$ -component, so $|a|^2 + |b|^2 = 1$.

To obtain the spin structure of the matrix element for the process $\bar{p} + p \to \phi + \pi^0$, using this model of nucleon, it is necessary to introduce more detailed assumptions about the reaction mechanism. One such assumption, which seems to be most natural, concerns transfering spin properties of $s\bar{s}$ (inside the nucleon) to the produced ϕ-meson. We shall assume that ϕ-meson conserves polarization of the initial $s\bar{s}$ component. This means that in (12) we can substitute $\mathbf{S} \to \mathbf{U}$ where $\mathbf{U}$ is 3-vector of ϕ-meson polarization.

So, we can conclude that such a nucleon must produce the ϕ-mesons, with polarization properties which are strongly correlated with the spin states of annihilating $\bar{p}p$-system. Thus, triplet states produce transversally polarized V-mesons, whereas singlet states produce longitudinally polarized ones. As a result we can obtain for the process $\bar{p} + p \to \phi + \pi$ (at $\theta = \pi/2$) the following predictions for the corresponding amplitudes:

$$h_1 = h_2,\ h_3 \neq 0. \tag{18}$$

The amplitude $h_1(h_3)$ must be determined by the constant a(b) in (17).

For testing these predictions, the spin correlation coefficients seem to be suitable, as we have in this case,

$$\begin{aligned} \mathcal{A}_{mm} &= -1, \\ \mathcal{A}_{nn} = \mathcal{A}_{kk} &= \frac{-2|h_1|^2 + |h_3|^2}{2|h_1|^2 + |h_3|^2}, \\ \mathcal{A}_{mk} = \mathcal{A}_{km} &= 0. \end{aligned} \tag{19}$$

Noting that $\rho_3 = |h_3|^2/(2|h_1|^2 + |h_3|^2)$, using (18), one finds

$$\mathcal{A}_{nn} = \mathcal{A}_{kk} = -1 + 2\rho_2. \tag{20}$$

One can see that, these polarization effects can discriminate between both possible predictions for amplitudes, namely (14) in the case of triplet dominance, and (18) for the specific model of nucleon with non-perturbative $s\bar{s}$ component.

4 Conclusions

We found the spin structure of the amplitude for the processes $\bar{p} + p \to P^0 + V^0$ under specific kinematical conditions at $\theta = \pi/2$, where C-invariance of strong interactions reduces the number of independent amplitudes to three. We analyzed the problem of a complete experiment choosing a parametrization of matrix elements in terms of the transversal amplitudes. We have suggested two steps for realization of such an experiment, namely the determination of the moduli of all the amplitudes as the first step, and the two relative phases of these amplitudes as the second step.

The polarization effects in $\bar{p} + p \to P^0 + V^0$ may be a good testing ground of the hypothesis of enhancement of strange particle production in NN or $N\bar{N}$ collisions quantitatively. There exists definite experimental evidence of the triplet nature of the $p\bar{p}$ interaction for the $\bar{p}+p \to \bar{\Lambda}+\Lambda$ process [22], and the hidden strangeness in $\bar{p}+p \to \phi+\pi^0$. Further testing must be based on the study of polarization transfer, from initial proton to the final hyperon in $\bar{p} + p \to \bar{\Lambda} + \Lambda$ [23]. This will provide information for the Q^2 dependence of the relative direction of spin of $s\bar{s}$ component of nucleon. Let us also note that existing new data [22] about the correlations of Λ and $\bar{\Lambda}$ polarizations in $\bar{p} + p \to \bar{\Lambda} + \Lambda$ support a positive value for this depolarization coefficient.

Therefore, additional polarization experiments are necessary and $\bar{p} + p \to \phi + \pi^0$ and $\bar{p} + p \to K^* + \bar{K}$ seem to be the most suitable process for such a study.

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