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A possibility to determine the P-parity of the Θ^+ pentaquark in the NN $\to Y\Theta^+$ reaction

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Abstract

Spin structure of the reaction $\vec{N}\vec{N} \to \vec{Y}\Theta$ is analyzed at the threshold in a model independent way for an arbitrary spin of the Θ^+. We found that the sign of the spin–spin correlation parameter $C_{x,x}$ being measured in a double-spin experiment, determines the P-parity of the Θ^+ unambiguously. Furthermore we show that the polarization transfer from a nucleon to the final hyperon Y is zero or non-zero strictly depending on the P-parity of the Θ^+ and the total isospin of the NN system. It allows one to determine the P-parity of the Θ^+ in a single-spin measurement, since the polarization of the Y can be measured via its weak decay.

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Keywords: Pentaquark; Strangeness; Spin observables

1. Introduction

The recent experimental discovery of an exotic baryon with a positive strangeness $S = +1$ and surprisingly narrow width [1–6], called now as the $\Theta^+(1540)$, stimulated many theoretical works concerning its structure. The quantum numbers of this baryon such as spin, parity and isospin are not yet determined experimentally. According to the original prediction within the chiral soliton model [7], the pentaquark Θ^+ belongs to the anti-decuplet with all members having one the same spin-parity, namely $J^P = \frac{1}{2}^+$. From the point of view of constituent quark model the minimal number of quarks in the Θ^+ is five, i.e., the quark content of this baryon is $uudd\bar{s}$. Within a quark-shell model with non-interacting quarks, the ground state of the Θ^+ is expected to be the $(1s)^5$-state, therefore the P-parity of the Θ^+ has to be negative, $\pi_\Theta = -1$. Inclusion of the special type of qq-interaction into the quark model could lead to the positive parity [8,9]. Diquark model [10] predicts also $\pi_\Theta = +1$. The lattice QCD calculation predicts for this baryon $\pi_\Theta = -1$ in Ref. [11], but gives $\pi_\Theta = +1$ according to Ref. [12]. So, the P-parity of the Θ^+ is a key point for quark dynamics and for the present the only way to get it is an experiment.

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Several methods based on dynamical assumptions were suggested for determination of the P-parity of the Θ^+ [13]. According to a general theorem [14], in order to determine the parity of one particle in a binary reaction one has to know polarizations at least of two fermions participating in this reaction. Model independent methods for determination of the P-parity of the Θ^+ were suggested recently in Refs. [15,16] for pp-collision, and in Ref. [17] for photoproduction of the Θ^+. The method of Refs. [15,16], based on the assumption that the spin of the Θ^+ equals $\frac{1}{2}$, suggests to measure the spin–spin correlation parameter in the reaction $\vec{p}\vec{p} \to \Sigma^+\Theta^+$ near the threshold. We generalize here this method for an arbitrary spin of the Θ^+ and both isospins $T = 0$ and $T = 1$ of the NN channel of the NN $\to Y\Theta^+$ reaction. Furthermore, we consider a polarization transfer from a nucleon to the hyperon Y in this reaction. Our consideration is model independent, since it is based only on conservation of the P-parity, total angular momentum and isospin in the reaction and the generalized Pauli principle for nucleons.

2. General case

We consider here the binary reaction $1 + 2 \to 3 + 4$ at the threshold region with an excess energy less than ten MeV, assuming a short-range type of the final state interaction. At this condition the S-wave presumably dominates in the final state, and therefore the most general expression for the amplitude of this reaction can be written as [18][1]

$$T^{\mu_3\mu_4}_{\mu_1\mu_2} = \sum_{JMSL} (j_1\mu_1 j_2\mu_2|SM)(j_3\mu_3 j_4\mu_4|JM) \times (SML0|JM)\sqrt{\frac{2L+1}{4\pi}}a^{LS}_J. \tag{1}$$

Here j_i and μ_i are the spin of the ith particle and its z-projection, J and M are the total angular momentum and its z-projection; S and L are the spin and orbital momentum of the initial system, respectively. The z-axis is directed here along the vector of the initial momentum $\mathbf{k}$. Information on the reaction dynamics is contained in the complex amplitudes a^{LS}_J. The sum over J in Eq. (1) is restricted by the conditions $J = j_3 + j_4, j_3 + j_4 - 1, \ldots, |j_3 - j_4|$. Due to P-parity conservation, the orbital momentum L in Eq. (1) is restricted by the condition $(-1)^L = \pi$, where $\pi = \pi_1\pi_2\pi_3\pi_4$ is the product of internal parities of the participating particles, π_i. We consider here mainly transitions without mixing the total isospin T in this reaction.[2] For the fixed T and π the spin of the initial nucleons S is fixed unambiguously by the generalized Pauli principle: $(-1)^S = \pi(-1)^{T+1}$. Therefore, in order to determine the P-parity π of the system at a given isospin T, it is sufficient to determine the spin S of the initial NN system.

At $j_1 = j_2 = \frac{1}{2}$ the number of the amplitudes a^{LS}_J depends on the spins j_3 and j_4. For a particular case of $j_3 = \frac{1}{2}$ and j_4 being half-integer, $j_4 = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$, there are two total angular momenta $J_p = j_4 + \frac{1}{2}$ and $J_m = j_4 - \frac{1}{2}$. For the spin-singlet initial state $S = 0$, only one orbital momentum is allowed, $L = J$, and therefore there is one scalar amplitude, $a^{LS}_J = a^{J0}_J$. For $S = 1$ and $j_4 \geqslant \frac{3}{2}$ there are three scalar amplitudes $a^{LS}_J \equiv a^L_J$:

(i) $a^{J_p}_{J_p}$, $a^{J_m+1}_{J_m}$ and $a^{J_m-1}_{J_m}$, if $(-1)^{J_p} = \pi$, or
(ii) $a^{J_m}_{J_m}(J_m \neq 0)$, $a^{J_p+1}_{J_p}$ and $a^{J_p-1}_{J_p}$, if $(-1)^{J_p} = -\pi$.

In order to simplify the notations, we omit here and below the superscript $S = 1$ in a^{LS}_J. For the case of $j_4 = j_3 = \frac{1}{2}$, one has $J_m = 0$ and $J_p = 1$. For this case only two triplet amplitudes are allowed for $\pi = +1$, i.e., a^0_1 and a^2_1, whereas the amplitude a^0_0 is forbidden by conservation of the total angular momentum. For $\pi = -1$ one has also only two triplet amplitudes, one of them corresponds to $J = 1$, a^1_1, and another one is allowed for $J = 0$, i.e., a^1_0.

According to a general method of Ref. [19], the amplitude of the reaction can be written as a matrix element of the following operator

[1] Higher partial waves can be easily included in this formalism (see Ref. [19]). However, due to unknown relative strength of the different waves the results for observables become model dependent above the threshold and not considered here.

[2] The isospin mixing is possible, for example, in the reaction $p + n \to \Sigma^0 + \Theta^+$, if the Θ^+ is an isotriplet. In this case the P-parity cannot be determined by means of the method in question.

$$\hat{F} = \sum_{m_1 m_2 m_3 m_4} T^{m_3 m_4}_{m_1 m_2} \chi^{+}_{j_1 m_1}(1) \chi^{+}_{j_2 m_2}(2) \times \chi_{j_3 m_3}(3) \chi_{j_4 m_4}(4), \tag{2}$$

where $\chi_{j_k m_k}(k)$ is the spin function of the kth particle with the spin j_k and z-projection m_k and $T^{m_3 m_4}_{m_1 m_2}$ is defined by Eq. (1). The operator $\hat{F}$ is normalized to the unpolarized cross section $d\sigma_0$ as

$$d\sigma_0 = \frac{\Phi}{(2j_1+1)(2j_2+1)} SpFF^{+} = \frac{1}{16\pi} \Phi \sum_{J,L} (2J+1) \left| a^{LS}_J \right|^2, \tag{3}$$

where Φ is a phase-space factor; we put here $j_1 = j_2 = \frac{1}{2}$.

Polarization transfer coefficient is given by the following formula [20]

$$K^{\kappa}_{\lambda} = \frac{SpF\sigma_{\lambda}(1)F^{+}\sigma_{\kappa}(3)}{SpFF^{+}}, \tag{4}$$

where $\lambda, \kappa = 0, \pm 1$. Using a technique of the spin-tensor operators [21], we find from Eqs. (1), (2) and (4) the following general formula:

$$\begin{aligned} SpFF^{+}K^{\kappa}_{\lambda} &= \delta_{\lambda,-\kappa} \frac{3}{2\pi} \sum_{SS'JJ'LL'J_0} \sqrt{(2L+1)(2L'+1)} \\ &\times \sqrt{(2S+1)(2S'+1)}(2J+1)(2J'+1) \\ &\times (-1)^{j_2+j_4+S'+J'+L} (1-\lambda 1 \lambda | J_0 0) \\ &\times (L'0L0|J_0 0) \\ &\times \begin{Bmatrix} \frac{1}{2} & j_2 & S \\ S' & 1 & \frac{1}{2} \end{Bmatrix} \begin{Bmatrix} \frac{1}{2} & j_4 & J' \\ J & 1 & \frac{1}{2} \end{Bmatrix} \begin{Bmatrix} J & S & L \\ J' & S' & L' \\ 1 & 1 & J_0 \end{Bmatrix} \\ &\times a^{LS}_J \left(a^{L'S'}_{J'} \right)^{*}. \end{aligned} \tag{5}$$

Here the standard notations for the $6j$-and $9j$-symbols are used [21] and a sum over allowed angular momenta is performed, as explained after Eq. (1), with $J_0 = 0$ and 2. From Eq. (5) one can find the following relations: $K^{-1}_{+1} = K^{+1}_{-1} = -K^{x}_{x} = -K^{y}_{y}$, and $K^{j}_{i} = 0$ at $i \neq j$, where $i, j = x, y, z$. For the spin-singlet state $S = S' = 0$, we find from Eq. (5) that there is no polarization transfer ($K^{j}_{i} = 0$, $i, j = x, y, z$). On the contrary, for the spin-triplet state $S = S' = 1$, Eq. (5) leads to non-zero diagonal terms $K^{x}_{x} = K^{y}_{y} \neq 0$ and $K^{0}_{0} = K^{z}_{z} \neq 0$. This is one of the most important features of the reaction in question. We emphasize that Eq. (5) is valid for $\pi = +1$ and $\pi = -1$ and for arbitrary spins j_2 and j_4 both of them being integer or half-integer. As an example, we consider here a case with the minimal spins $j_i = \frac{1}{2}$ ($i = 1, \ldots, 4$) for $S = 1$. In this case, for $T = 0$ and $\pi = +1$ Eq. (5) gives

$$K^{x}_{x} = K^{y}_{y} = \frac{|\sqrt{2}a^{0}_{1} + a^{2}_{1}|^2 - 3\,\mathrm{Re}(\sqrt{2}a^{0}_{1} + a^{2}_{1})a^{2*}_{1}}{3(|a^{0}_{1}|^2 + |a^{2}_{1}|^2)}, \tag{6}$$

$$K^{z}_{z} = \frac{|\sqrt{2}a^{0}_{1} + a^{2}_{1}|^2}{3(|a^{0}_{1}|^2 + |a^{2}_{1}|^2)}. \tag{7}$$

For $T = 1$ and $\pi = -1$ one has got from Eq. (5)

$$K^{x}_{x} = K^{y}_{y} = \frac{\sqrt{6}\,\mathrm{Re}\, a^{1}_{0} a^{1*}_{1}}{|a^{1}_{0}|^2 + 3|a^{1}_{1}|^2}, \qquad K^{z}_{z} = \frac{3|a^{1}_{1}|^2}{|a^{1}_{0}|^2 + 3|a^{1}_{1}|^2}. \tag{8}$$

For higher spins of the 4th particle $j_4 \geqslant \frac{3}{2}$ and $S = 1$, one can find from Eq. (5) that the coefficients $K^{x}_{x} = K^{y}_{y}$ and K^{z}_{z} are, in general case, also non-zero.

The spin–spin correlation coefficient is defined as [20]

$$C_{\lambda,\kappa} = \frac{SpF\sigma_{\lambda}(1)\sigma_{\kappa}(2)F^{+}}{SpFF^{+}}. \tag{9}$$

Using Eqs. (9), (1) and (2) we find the following relations: $C_{+1,-1} = C_{-1,+1} = -C_{x,x} = -C_{y,y} \neq 0$, $C^{0}_{0} = C^{z}_{z} \neq 0$, whereas $C_{i,j} = 0$ at $i \neq j$ ($i, j = x, y, z$). Furthermore, for the spin-singlet state $S = S' = 0$ one has

$$C_{x,x,} = C_{y,y} = C_{z,z} = -1. \tag{10}$$

For the spin-triplet initial state $S = 1$ we find

$$C_{x,x} = C_{y,y} = \frac{\sum_J |\sqrt{J}a^{J-1}_{J} - \sqrt{J+1}a^{J+1}_{J}|^2}{\sum_{JL}(2J+1)|a^{L}_{J}|^2}, \tag{11}$$

$$C_{z,z} = 1 - 2C_{y,y}. \tag{12}$$

As seen from Eq. (11), for $S = 1$ the spin–spin correlation parameters are non-negative for transversal polarization for arbitrary spins j_3 and j_4 both of them being integer or half-integer. This is the second important feature of this reaction. On the contrary, the sign of $C_{z,z}$ can be positive or negative depending on dynamics.

3. The case of minimal spins

For the particular case of $j_1 = j_2 = j_3 = j_4 = \frac{1}{2}$ one can check the above results, using a $\boldsymbol{\sigma}$-representation for the amplitude Eq. (1), and obtain on this way all the spin observables of this reaction. We discuss here only the case of $T = 0$, since the another case $T = 1$ was analyzed in Refs. [15,16]. For $T = 0$ and $\pi = -1$, one has $S = 0$. In this case the amplitude (1) describes the ${}^1P_1 \to {}^3S_1$ transition and can be given by

$$T^{\mu_3\mu_4}_{\mu_1\mu_2} = \sqrt{\frac{3}{16\pi}}(\mathbf{T}' \cdot \hat{\mathbf{k}}) S a_1^{10}, \tag{13}$$

where $\mathbf{T}' = i(\chi^+_{\mu_3}\boldsymbol{\sigma}\sigma_y\chi^{(T)+}_{\mu_4})$, $S = -i(\chi^T_{\mu_1}\sigma_y\chi_{\mu_2})$, $\boldsymbol{\sigma}$ is the Pauli spin matrix, χ_{μ_j} is the 2-spinor for the jth particle with the spin projection μ_j and $\hat{\mathbf{k}}$ is the unit vector along the beam direction. Using Eq. (13), one can find the cross section with polarized particles in the initial and final states as

$$\begin{aligned} d\sigma(\mathbf{p}_1, \mathbf{p}_2; \mathbf{p}_3, \mathbf{p}_4) &= \Phi |M^{\mu_3\mu_4}_{\mu_1\mu_2}|^2 \\ &= \frac{1}{4} d\sigma_0 (1 - \mathbf{p}_1 \cdot \mathbf{p}_2) \\ &\quad \times \big[1 + \mathbf{p}_3 \cdot \mathbf{p}_4 - 2(\mathbf{p}_3 \cdot \hat{\mathbf{k}})(\mathbf{p}_4 \cdot \hat{\mathbf{k}})\big], \end{aligned} \tag{14}$$

where $d\sigma_0$ is given by Eq. (3) and $\mathbf{p}_i$ is the polarization vector of the ith particle. The polarization vectors of the final particles $\mathbf{p}_3$ and $\mathbf{p}_4$ are determined by the reaction amplitude (13) and can be found using the standard methods [19,20]. When substituting the obtained vectors $\mathbf{p}_3$ and $\mathbf{p}_4$ into Eq. (14), one can find the polarized cross section $d\sigma(\mathbf{p}_1, \mathbf{p}_2)$ as

$$d\sigma(\mathbf{p}_1, \mathbf{p}_2) = d\sigma_0 (1 - \mathbf{p}_1 \cdot \mathbf{p}_2). \tag{15}$$

However, the calculation of $\mathbf{p}_3$ and $\mathbf{p}_4$ is not necessarily here because Eq. (14) contains all spin observables of this reaction. For example, one can find from Eq. (14) the initial spin–spin correlation as $C_{x,x} = C_{y,y} = C_{z,z} = -1$ and, furthermore, a certain spin–spin correlation in the final state.

For $T = 0$ and $\pi = +1$ one has $S = 1$. In this case Eq. (1) describes the ${}^3S_1 - {}^3D_1 \to {}^3S_1$ transition and can be written as

$$T^{\mu_3\mu_4}_{\mu_1\mu_2} = \frac{1}{\sqrt{16\pi}}\big[G(\mathbf{T}' \cdot \mathbf{T}) + F(\mathbf{T}' \cdot \mathbf{k})(\mathbf{T} \cdot \mathbf{k})\big], \tag{16}$$

where $\mathbf{T} = -i(\chi^T_{\mu_1}\sigma_y\boldsymbol{\sigma}\chi_{\mu_2})$. The form factors G and F are given here by $G = a_1^0 + \frac{1}{\sqrt{2}}a_1^2$ and $F = -\frac{3}{\sqrt{2}}a_1^2$. The polarized cross section for this case is

$$\begin{aligned} &d\sigma(\mathbf{p}_1, \mathbf{p}_2; \mathbf{p}_3, \mathbf{p}_4) \\ &\quad = \frac{\Phi}{4\pi} \sum_{\alpha\beta = x,y,z} \frac{1}{8} Sp\big\{\sigma_\alpha(1 - \boldsymbol{\sigma}\cdot\mathbf{p}_4)\sigma_\beta(1 + \boldsymbol{\sigma}\cdot\mathbf{p}_3)\big\} \\ &\qquad \times \frac{1}{8} Sp\big\{\Pi^+_\alpha(1 + \boldsymbol{\sigma}\cdot\mathbf{p}_2) \\ &\qquad \times \Pi_\beta(1 - \boldsymbol{\sigma}\cdot\mathbf{p}_1)\big\}, \end{aligned} \tag{17}$$

where Π_α $(\alpha = x, y, z)$ is the following spin operator

$$\Pi_\alpha = G\sigma_\alpha + F\hat{k}_\alpha(\boldsymbol{\sigma} \cdot \hat{\mathbf{k}}). \tag{18}$$

We do not present here the final long formula completely, since not all its terms are necessary for the present discussion. As an example, we take the terms arising in front of the structures $\mathbf{p}_1 \cdot \mathbf{p}_3$ and $(\mathbf{p}_1 \cdot \hat{\mathbf{k}})(\mathbf{p}_3 \cdot \hat{\mathbf{k}})$ in the right-hand side of Eq. (17), i.e., the polarization transfer coefficients

$$\begin{aligned} K^x_x = K^y_y &= 2\frac{|G|^2 + \operatorname{Re} GF^*}{|G+F|^2 + 2|G|^2}, \\ K^z_z &= 2\frac{|G|^2}{|G+F|^2 + 2|G|^2}, \end{aligned} \tag{19}$$

and $K^j_i = 0$ at $i \neq j$ $(i, j = x, y, z)$. These formulae coincide with those, given by Eqs. (6) and (7), respectively. From Eqs. (14) and (17) one can find that for unpolarized beam (or target), the polarizations of the final particles are zero and the analyzing power is also zero for any P-parity π.

4. Discussion and conclusion

(1) As it follows from Eqs. (11) and (12), the coefficients $C_{x,x}$ and $C_{y,y}$ are non-negative for $S = 1$. On the other hand, these observables are equal to -1 for $S = 0$ (see Eq. (10)). This result does not depend on the mechanism of the reaction and the spin of the pentaquark, j_Θ, and therefore allows one to determine the P-parity unambiguously in double-spin measurements with transversely polarized beam and target. A similar conclusion was made in Refs. [15, 16], but for the particular case of $j_\Theta = \frac{1}{2}$ and $T = 1$.

(2) As follows from Eqs. (5)–(8), for polarized beam (or target) the final particle is polarized along

the direction of the initial polarization vector, if the initial state is the spin-triplet one. The sign and the absolute value of the spin-transfer coefficients depend on the relative strength of the different amplitudes a_J^{LS} and therefore cannot be calculated without further dynamical assumptions. For the spin-singlet initial state the polarization transfer is zero. Thus, a measurement of the polarization of one final particle in the reaction $\vec{N}N \to Y + \Theta^+$ allows one to determinate the P-parity of the Θ^+ in a largely model-independent way.[3] The polarization of the final hyperon can be measured by a measurement of the angular distribution in its weak decay. The reaction $pn \to \Lambda^0\Theta^+$ seems rather attractive, since in the decay $\Lambda^0 \to \pi^- + p$ both the final particles are charged, and due to P-parity violation there is a large asymmetry in their angular distribution in the c.m.s. of the Λ^0 in respect of the direction of the Λ^0 spin. Since the polarization of Σ^+ is also self-analyzing via its decays $\Sigma^+ \to p + \pi^0$ or $\Sigma^+ \to n + \pi^+$, the polarization transfer in the reaction $\vec{p}p \to \vec{\Sigma}^+\Theta^+$ can be used for the P-parity determination too (see, for example, Eq. (8)). At some experimental conditions such single-spin experiments are, probably, more simple than the double-spin measurements in the $\vec{p}\vec{p} \to \Sigma^+\Theta^+$ or $\vec{p}\vec{n} \to \Lambda^0\Theta^+$ reactions. According to recent estimations [22] performed in the Born approximation for kaon exchanges, the cross section of the reaction $pn \to \Lambda^0\Theta^+$ near the threshold is by factor of ten higher as compared to $pp \to \Sigma^+\Theta^+$. At present, a measurement of K_y^y in the reaction $\vec{p}d \to \vec{\Lambda}^0 + \Theta^+ + p_s$ is possible at COSY. At low momenta of the spectator proton p_s less than ≈ 50 MeV$/c$, the excess energy in the reaction $pn \to \Lambda^0\Theta^+$ is less than 50 MeV. It is enough low to use $C_{x,x}$ for P-parity determination [16,22]. Furthermore, as known from the $d(p,2p)n$ reaction [23], the initial and final state interactions affect spin observables rather weakly in the quasi-free region.

(3) Most likely, the Θ^+ is an isosinglet, since the isospin partner Θ^{++} was not observed in γp interaction [4,5]. This assumption can be verified by polarization measurements in question. Due to the relation $(-1)^{S+T} = -\pi_\Theta$, the total isospin of the NN channel T determines the spin observables of the reaction NN $\to Y\Theta^+$ in the same way as the P-parity of the Θ^+, π_Θ. As we found, the spin observables K_i^j and $C_{i,j}$ *at given* T are changed drastically, when π_Θ changes from $+1$ to -1. This is because the sign of π_Θ determines unambiguously the initial spin S. On the other side, the same strong changing of the spin observables appears *at given* π_Θ, when the total isospin T of the NN-system is changed. Thus, if the Θ^+ is the isosinglet, measured spin observables in the reactions $pp \to \Sigma^+\Theta^+$ $(T = 1)$ and $pn \to \Lambda^0\Theta^+$ $(T = 0)$ must be different. We assume here that Λ^0 is the isosinglet. However, if the isospin of the Θ^+ is equal to 1 (or an isotriplet Θ^* from the 27-plet is under consideration), then one has $T = 1$ in the reaction $pn \to \Lambda^0\Theta^+$. In this case the spin observables of the reaction $pn \to \Lambda^0\Theta^+$ are identical with those for the reaction $pp \to \Sigma^+\Theta^+$. Thus, a combined measurement of the above spin observables in these two reactions allows one to determine both the P-parity and isospin of the Θ^+. If the isospin of the Θ^+ equals 2 [24], the reaction $pn \to \Lambda^0\Theta^+$ is forbidden due to isospin conservation in strong interactions.

In conclusion, there are two model-independent features of the reaction NN $\to Y\Theta^+$ near the threshold. Firstly, for the initial spin-triplet state the spin–spin correlation parameter $C_{y,y}$ is non-negative, and the polarization transfer coefficients K_x^x and K_z^z are non-zero. Secondly, for $S = 0$ the $C_{y,y}$ is equal to -1 and the polarization transfer is absent. Both these signals do not depend on the spin of the Θ^+ and can be used for unambiguous determination of the P-parity and isospin of the Θ^+ in the reactions $pn \to \Lambda^0\Theta^+$ and $pp \to \Sigma^+\Theta^+$. The method is rather general and can be applied for P-parity determination of others baryons with arbitrary spins.

Note added

After the original submission of this Letter, the papers [25] appeared, where the same subject is studied in a different formalism.

[3] We assume here that there is no accidental cancellation between the different amplitudes a_J^L and therefore $K_x^x \neq 0$ and $K_z^z \neq 0$ for $S = 1$. In order to exclude such a cancellation experimentally, one should repeat measurement at different beam energies, doing it, probably, for the both $T = 1$ and $T = 0$ channels.

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