Possible methods for the determination of the P-parity of the Θ^+-pentaquark in NN-collisions.

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Abstract

We present two possibilities to determine the P-parity of the pentaquark Θ^+, in a model independent way, via the measurement of polarization observables in $p+p \to \Theta^+ + \Sigma^+$, or $n+p \to \Theta^+ + \Lambda^0$, in the near threshold region. Besides the measurement of the spin correlation coefficient, $A_{xx} = A_{yy}$, (in collisions of transversally polarized nucleons), the coefficient D_{xx} of polarization transfer from the initial proton to the final $\Sigma^+(\Lambda^0)$ hyperon is also unambiguously related to the Θ^+ parity.

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In 1999, N. K. Pak and M. Rekalo proposed [1] two new methods for the determination of the P-parity of the K-meson, through the measurement of different polarization observables in K-meson production in proton proton collisions near threshold, $p + p \to K^+ + Y^0 + p$ ($Y^0 = \Lambda$ or Σ-hyperon). One method is based on the measurement of the sign of the spin correlation coefficient A_{yy}, for collisions of transversally polarized protons. The second one is based on the measurement of the polarization transfer coefficient from the initial proton to the produced hyperon, D_{nn}. Both methods apply in threshold conditions, where all final particles are in S-state. Note, in this respect, that the DISTO collaboration showed the feasibility of the second method, by measuring the D_{nn} coefficient at proton momentum of 3.67 GeV/c, which showed that *"D_{nn} is large and negative ($\simeq -0.4$) over most of the kinematic region"* [2]. It was mentioned in [1] that a nonzero value of D_{nn}, in the threshold region, can be considered as the experimental confirmation of the pseudoscalar nature of the K^+ meson.

It is straightforward to adapt these methods to the determination of the P-parity of the Θ^+-hyperon, which is presently object of an intensive theoretical discussion.

The simplest reactions of NN-collisions, which can be considered for this aim are the following:

$$p + n \to \Lambda^0 + \Theta^+, \tag{1}$$

$$p + p \to \Sigma^+ + \Theta^+, \tag{2}$$

$$p + p \to \pi^+ + \Lambda^0 + \Theta^+, \tag{3}$$

in threshold conditions (S-wave production). It is important to note that the Λ^0 or the Σ^+ hyperons, produced in these reactions, are self analyzing particles, therefore the polarization transfer method - with measurement of the polarization transfer coefficient D_{nn} seems more preferable, from the experimental point of view.

The following analysis of reactions (1-3) is based on general symmetry properties of the strong interaction, such as the P-invariance, the conservation of the total angular momentum, the Pauli principle, for the pp-system, and the generalized Pauli principle for the np system, which holds at the level of the isotopic invariance of the strong interaction.

These symmetry properties, being applied to S-wave production in the processes (1-3) allow to establish the spin structure of the corresponding matrix elements, for both cases of the considered P-parity.

We consider here, for simplicity, the case of spin 1/2 Θ^+ hyperon, but this formalism can be extended to any Θ^+ spin.

Firstly, let us establish the general spin structure of double polarization observables for the processes (1-3) at threshold.

The dependence of the cross section, total or differential, on the polarizations $\vec{P}_1$ and $\vec{P}_2$ of the colliding nucleons can be written as:

$$\sigma(\vec{P}_1, \vec{P}_2) = \sigma_0(1 + \mathcal{A}_1 \vec{P}_1 \cdot \vec{P}_2 + \mathcal{A}_2 \hat{\vec{k}} \vec{P}_1 \cdot \hat{\vec{k}} \vec{P}_2), \tag{4}$$

where σ_0 is the cross section for the collision of unpolarized nucleons, $\hat{\vec{k}}$ is the unit vector along the three momentum of the colliding nucleons, in the reaction CM system. The real coefficients $\mathcal{A}_1$ and $\mathcal{A}_2$, which are different for different reactions, depend on the parity of the Θ^+ hyperon. Taking the z-axis along $\hat{\vec{k}}$, one can find the following expression for the spin correlation coefficients $\mathcal{A}_{ab}$, in terms of $\mathcal{A}_1$ and $\mathcal{A}_2$:

$$\mathcal{A}_{xx} = \mathcal{A}_{yy} = \mathcal{A}_1, \ \mathcal{A}_{zz} = \mathcal{A}_1 + \mathcal{A}_2. \tag{5}$$

The dependence of the polarization $\vec{P}_Y$ of the produced hyperon, Λ or Σ^+, on the polarization $\vec{P}$ of the initial nucleon (beam or target) can be written as:

$$\vec{P}_Y = p_1 \vec{P} + p_2 \hat{\vec{k}} \ \hat{\vec{k}} \cdot \vec{P}, \tag{6}$$

where $p_{1,2}$ are real coefficients, which depend on the Θ^+ parity, so that for the non-zero polarization transfer coefficients, D_{ab} one can write:

$$\mathcal{D}_{xx} = \mathcal{D}_{yy} = p_1, \ \mathcal{D}_{zz} = p_1 + p_2. \tag{7}$$

Let us calculate these coefficients for the reactions (1-3), it terms of S-wave partial amplitudes, considering both values of the Θ^+ parity.

$\underline{n + p \to \Lambda + \Theta^+}$. This reaction has the lowest threshold, and seems very interesting for the measurement of the $\mathcal{D}_{nn}$ coefficient, due to the large asymmetry and branching ratio of the decay $\Lambda \to p + \pi^-$ ($\alpha = 0.642 \pm 0.013$ and Br=$(63.9 \pm 0.5)\%$ [3]).

The spin structure of the threshold matrix element depends on the discussed P-parity (assuming that the isotopic spin of Θ^+ is zero):

$$\mathcal{M}_\Lambda^{(-)} = f^{(-)}(\Lambda) \mathcal{I} \bigotimes \vec{\sigma} \cdot \hat{\vec{k}}, \ \ \text{if } P(\Theta^+) = -1, \tag{8}$$

$$\mathcal{M}_\Lambda^{(+)} = f_1^{(+)}(\Lambda)\vec{\sigma}\cdot\hat{\vec{k}}\bigotimes\vec{\sigma}\cdot\hat{\vec{k}} + f_2^{(+)}(\Lambda)(\sigma_m - \hat{k}_m\sigma\cdot\hat{\vec{k}})\bigotimes\sigma_m, \text{ if } P(\Theta^+) = +1 \quad (9)$$

where the upper index $(\pm)$ for the partial amplitudes $f(\Lambda)$ corresponds to $P(\Theta^+) = \pm 1$. Henceforward we use the following abbreviation

$$A\bigotimes B = (\tilde{\chi}_2\sigma_y A\chi_1)(\chi_4^\dagger B\sigma_y\tilde{\chi}_3^\dagger), \quad (10)$$

where χ_1 and χ_2 (χ_3 and χ_4) are the two-component spinors of the initial (final) baryons.

Using Eqs. (8) and (9) one can find the following formulas for double spin polarization observables:

$$\mathcal{A}_{xx}^{(-)}(\Lambda) = \mathcal{A}_{yy}^{(-)}(\Lambda) = \mathcal{A}_{zz}^{(-)}(\Lambda) = -1,\ \mathcal{D}_{ab}^{(-)} = 0, \text{ if } P(\Theta^+) = -1, \quad (11)$$

and

$$D_\Lambda^{(+)}\mathcal{A}_{xx}^{(+)}(\Lambda) = D_\Lambda^{(+)}\mathcal{A}_{yy}^{(+)}(\Lambda) = |f_{1\Lambda}^{(+)}|^2,\ D_\Lambda^{(+)}\mathcal{A}_{zz}^{(+)}(\Lambda) = 2\left(-|f_1^{(+)}(\Lambda)|^2 + |f_2^{(+)}(\Lambda)|^2\right) \quad (12)$$

$$D_\Lambda^{(+)}\mathcal{D}_{xx}^{(+)}(\Lambda) = D_\Lambda^{(+)}\mathcal{D}_{yy}^{(+)}(\Lambda) = 2Ref_{1\Lambda}^{(+)}f_{2\Lambda}^{(+)*},\ D_\Lambda^{(+)}\mathcal{D}_{zz}^{(+)}(\Lambda) = 2|f_2^{(+)}(\Lambda)|^2, \quad (13)$$

with

$$D_\Lambda^{(+)} = |f_1^{(+)}(\Lambda)|^2 + 2|f_2^{(+)}(\Lambda)|^2, \text{ if } P(\Theta^+) = +1,$$

So, comparing the two possibilities for the P-parity, one can predict, in model independent way:

$$\mathcal{A}_{xx}^{(-)}(\Lambda) = \mathcal{A}_{yy}^{(-)}(\Lambda) = -1,\ \mathcal{D}_{yy}^{(-)}(\Lambda) = 0, \text{ if } P(\Theta^+) = -1,$$
$$\mathcal{A}_{yy}^{(+)}(\Lambda) \geq 0,\ \mathcal{D}_{yy}^{(-)}(\Lambda) \neq 0, \text{ if } P(\Theta^+) = +1 \quad (14)$$

with evident sensitivity of these observables to the parity of the Θ^+ hyperon.

$\underline{p + p \to \Sigma^+ + \Theta^{+}}$[1]. The spin structure of the threshold matrix element is different from Λ production (due to the difference in the value of the total isotopic spin for the colliding nucleons) and depends on $P(\Theta^+)$:

$$\mathcal{M}_\Sigma^{(+)} = f^{(+)}(\Sigma)\mathcal{I}\bigotimes\mathcal{I}, \text{ if } P(\Theta^+) = +1 \quad (15)$$

$$\mathcal{M}_\Sigma^{(-)} = f_1^{(-)}(\Sigma)\vec{\sigma}\hat{\vec{k}}\bigotimes\mathcal{I} + if_2^{(-)}(\Sigma)(\vec{\sigma}\times\hat{\vec{k}})_m)\bigotimes\sigma_m, \text{ if } P(\Theta^+) = -1 \quad (16)$$

where $f^{(\pm)}(\Sigma)$ are the corresponding partial amplitudes for $P(\Theta^+) = \pm 1$, in case of Σ production.

[1] The collisions of polarized protons in this reaction have been considered in [4].

Using these matrix elements, one can find the following form for the corresponding double polarization observables:

$$D_\Sigma^{(-)}\mathcal{A}_{xx}^{(-)}(\Sigma)=D_\Sigma^{(-)}\mathcal{A}_{yy}^{(-)}(\Sigma)=|f_1^{(-)}(\Sigma)|^2,$$

$$D_\Sigma^{(-)}\mathcal{A}_{zz}^{(-)}(\Sigma)=-|f_1^{(-)}(\Sigma)|^2+2|f_2^{(-)}(\Sigma)|^2,$$

$$D_\Sigma^{(-)}\mathcal{D}_{xx}^{(-)}(\Sigma)=D_\Sigma^{(-)}\mathcal{D}_{yy}^{(-)}(\Sigma)=2Ref_1^{(-)}(\Sigma)f_2^{(-)*}(\Sigma), \tag{17}$$

$$D_\Sigma^{(-)}\mathcal{D}_{zz}^{(-)}(\Sigma)=2|f_1^{(-)}(\Sigma)|^2,$$

with $D_\Sigma^{(-)}=|f_1^{(-)}(\Sigma)|^2+2|f_1^{(-)}(\Sigma)|^2$, in case of negative parity of the Θ^+, and

$$\mathcal{A}_{xx}^{(+)}(\Sigma)=\mathcal{A}_{yy}^{(+)}(\Sigma)=\mathcal{A}_{zz}^{(+)}(\Sigma)=-1,\ \mathcal{D}_{ab}^{(+)}(\Sigma)=0 \tag{18}$$

in case of positive parity.

Therefore, the measurement of the quantities $\mathcal{A}_{yy}(\Sigma)$ and $\mathcal{D}_{yy}(\Sigma)$ allows to determine the P-parity:

$$\mathcal{A}_{yy}^{(-)}(\Sigma)\geq 0,\ \mathcal{D}_{yy}^{(-)}(\Sigma)\neq 0\ \text{ if } P(\Theta^+)=-1$$

$$\mathcal{A}_{yy}^{(+)}(\Sigma)=-1,\ \mathcal{D}_{yy}^{(+)}(\Sigma)=0\ \text{ if } P(\Theta^+)=+1. \tag{19}$$

Comparing Eqs. (14) and (19), one can see that the reactions of Θ^+ production in NN-collisions, $p+p\to\Sigma^++\Theta^+$ and $n+p\to\Lambda^0+\Theta^+$, which look similar at first sight, show a very different dependence of the $\mathcal{A}_{yy}$ and $\mathcal{D}_{yy}$ observables on the P-parity of the Θ^+ hyperon. For example, the signs of $\mathcal{A}_{yy}(\Sigma)$ and $\mathcal{A}_{yy}(\Lambda)$ asymmetries are different, independently on $P(\Theta^+)$. A large difference is also present in the $\mathcal{D}_{yy}(\Sigma)$ and $\mathcal{D}_{yy}(\Lambda)$ observables.

$p+p+\to\pi^++\Lambda+\Theta^+$. The spin structure of the corresponding matrix elements can be written as follows:

$$\mathcal{M}^{(-)}=f^{(-)}\mathcal{I}\bigotimes\mathcal{I},\quad \text{if } P(\Theta^+)=-1$$

$$\mathcal{M}^{(+)}=f_1^{(+)}\vec{\sigma}\cdot\hat{\vec{k}}\bigotimes\mathcal{I}+if_2^{(+)}(\vec{\sigma}\times\hat{\vec{k}})_m\bigotimes\sigma_m,\quad \text{if } P(\Theta^+)=+1, \tag{20}$$

i.e. similar to the reaction $p+p\to\Sigma^++\Theta^+$, but with opposite parity. So, for $p+p\to\pi^++\Lambda+\Theta^+$, the necessary polarization observables can be described by Eqs.(17) and (18), taking care to interchange the P-parities.

This analysis shows that all the reactions (1-3) are well adapted to the determination of $P(\Theta^+)$. In all these reactions two polarization observables, namely $\mathcal{A}_{yy}$ and $\mathcal{D}_{yy}$ are sensitive

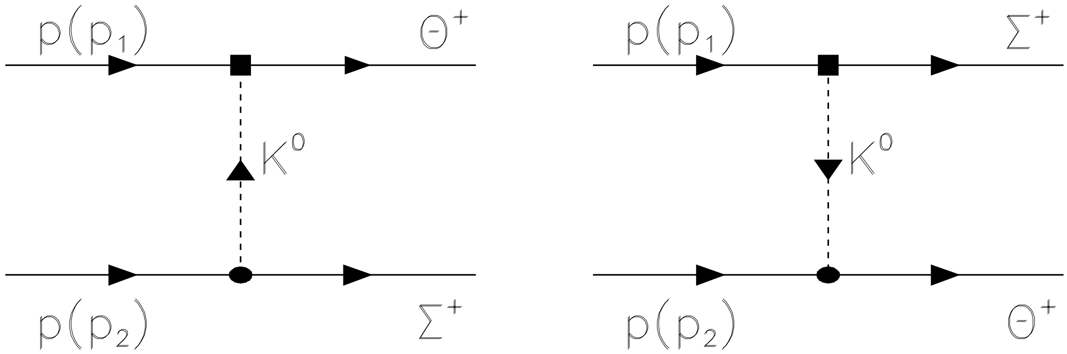

FIG. 1: K-exchange for the reaction $p + p \to \Sigma^+ + \Theta^+$.

to this parity. The signature of the parity of (Θ^+) is the sign of the asymmetry $\mathcal{A}_{yy}$, or a a value of the transfer polarization tensor, different from zero. These statements are model independent.

Let us briefly discuss the expected values of the polarization observables, in the reactions (1-3), which depend on two amplitudes, f_1 and f_2. For this aim, we will take, as an example, a model of K-meson exchange, which has been applied to the Λ and Σ^0 production in pp-collisions [5], and reproduces quite well the sign and the absolute value of D_{nn} in $\vec{p} + p \to \vec{\Lambda} + K^+ + p$. Considering the contribution of both diagrams in Fig. 1, one can find:

$$f_1^{(-)}(\Sigma) = -f_2^{(-)}(\Sigma) \tag{21}$$

This relation does not depend on many details of the reaction mechanism, such as the values of the two coupling constants, $g_{p\Theta K}$ and $g_{p\Sigma K}$, on the width of Θ^+ and on the form of the phenomenological form factors, which has to be taken into account in such considerations.

The relation (21) allows to predict:

$$\mathcal{A}_{yy}^{(-)}(\Sigma) = +1/3,\ \mathcal{D}_{yy}^{(-)}(\Sigma) = -2/3. \tag{22}$$

Let us note that $|\mathcal{D}_{yy}^{(-)}(\Sigma)|$ is different from zero and large. This will make easier to discriminate the value of the P-parity.

The same relation holds also for the amplitudes $f_{1,2}^{(+)}(\Lambda)$ for the process $n + p \to \Lambda + \Theta^+$ (for K-exchange), with corresponding predictions for polarization effects.

Note, however, that final state $\Sigma\Theta$- interaction, which is different, generally, in singlet and triplet states, can affect the relation (21). There are arguments which show that these effects can not be large [4]. In any case we considered here K-exchange only for illustrative purposes, for a quick estimation of polarization phenomena, without any claim that this is a realistic model for these reactions [6]: the main result of this paper does not depend on model considerations.

The experimental study of all three reactions (1-3) will give a non ambiguous signature of the Θ^+ parity.

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