# New experimental methods for the determination of the *P* parity of *K* mesons

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We propose new methods to determine the *P* parity of the *K* mesons experimentally, based on the measurement of polarization observables in *K*-meson production in polarized proton-proton collisions. The first method is based on the measurement of the sign of the spin correlation coefficient with transversally polarized protons. The second one is based on the measurement of the polarization transfer coefficient from the initial proton to the produced hyperon. [S0556-2821(99)01905-0]

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For the members of the pseudoscalar meson octet, the *P* parities (from this point on, we will refer to this as parity for short) of the neutral $\pi^0$ and $\eta$ mesons can be determined independently of the parities of the other particles. But the parities of charged pions makes sense only in a definite ''reference frame,'' where we can assign definite parities for, say, the proton and neutron.

The parity of $\pi^0$ mesons has been determined by measuring the correlation of polarizations of both photons produced in the decay $\pi^0 \to 2\gamma$, via $\pi^0 \to (e^+e^-)+(e^+e^-)$ [1]. The pseudoscalar nature of the $\eta$ meson follows from the fact that the decay $\eta \to \pi^+\pi^-$ is forbidden: $\mathrm{Br}(\eta \to \pi^+\pi^-) \leqslant 1.5\times 10^{-3}$ [2]. The parity of the negative pions has been determined in the reaction $\pi^- d \to nn$, induced by the capture of slow pions in the *s* state [3]. For the positive pions, one can simply assume $P_{\pi^+}=P_{\pi^-}$, using the general quantum field theory statement that the parity of any boson must be equal to that of the corresponding antiboson. From the experimental point of view, the process $e^+e^- \to \pi^+\pi^-$, which is used for measuring the electromagnetic form factor of pions, can be considered as evidence for $P_{\pi^+}=P_{\pi^-}$, or otherwise the vertex $\gamma^*\pi^+\pi^-$ ($\gamma^*$ is a virtual photon) would be forbidden by the parity conservation rule.

In the framework of the quark model for hadrons, one can for example assume that the parities of all three quarks $(u,d,s)$ are equal and positive. Because, of the conservation of the electric charge (in all interactions) and strangeness (in the strong, and electromagnetic interactions), it is impossible to find a process which allows one to compare the parities of $u,d$, and $s$ quarks experimentally. If the parities of the quarks were assumed to be the same, then, one can conclude that the parity of the $q\bar{q}$ system (in the *S* state) must be negative, as the internal parity of a fermion-antifermion system must be negative (Berestezky theorem [4]).

It would be good to prove that all four *K* mesons are pseudoscalar particles experimentally, without any specific model-dependent assumptions, such as the validity of quark model predictions concerning the internal parities of the $q\bar{q}$ systems. As all the decays of kaons are induced by the weak interactions, which does not conserve parity, weak decays are not suitable for the determination of the kaon parity. Therefore, for kaons it is necessary to consider processes induced by the strong or electromagnetic interactions. As the spin structures of the matrix elements for strong and electromagnetic processes depend on the internal properties of the particles involved, then it is natural to look at the polarization phenomena, and this is the approach adopted in this work.

It was indicated in Refs. [5,6], that the relative sign of the polarization of $\Lambda$ hyperon $P_\Lambda$ in the process $\pi^- p \to \Lambda K^0$, and the analyzing power $\mathcal{A}$ in $\pi^- \vec{p} \to \Lambda K^0$ (with a polarized hydrogen target) is related to the kaon parity $\mathcal{P}_K$ as $P_\Lambda = -\mathcal{P}_K \mathcal{A}$. This relation is obtained by using only the conservation of parity in strong interactions and the pseudoscalar character of the negative pion. Note that, in this case only the relative value of the kaon parity can be measured, in the reference frame with equal parities for proton and $\Lambda$ hyperon [this coincides with the above mentioned SU(3) system of reference, where the parities of all three quarks $u,d$, and $s$, are positive].

In Ref. [7] another method for the determination of kaon parity was mentioned, which is based on the observabilty of the reaction $K^- + {}^4\mathrm{He} \to {}^4_\Lambda H + \pi^0$. The crucial issue here is the spin of ${}^4_\Lambda H$. Assuming that it has zero spin, the conservation of angular momentum implies that the parity of the *K* must be the same as that of the pion. Note, however, that, sometimes the conclusion about the spin of ${}^4_\Lambda H$ is essentially based on the assumption that $K^-$ and $\pi^0$ should have equal *P* parities [8]. Furthermore, the method proposed in this work to determine the spin of ${}^4_\Lambda H$ which is based on the analysis of the decay ${}^4_\Lambda H \to {}^4\mathrm{He} + \pi^-$ involved an additional assumption that the $\Lambda$ hyperon in ${}^4_\Lambda H$ must be in *s* state only. Thus, one should not use the process $K^- + {}^4\mathrm{He} \to {}^4_\Lambda H + \pi^0$ for an independent determination of the kaon parity.

In this paper, we propose new experimental methods for direct determination of the kaon parity, taking advantage of the recently available advanced technology of polarized beams, polarized targets, and the effective polarimetry of produced particles. We will demonstrate how the measurement of the certain polarization characteristics in the process $\vec{p}+\vec{p} \to K+Y+N$, with $Y=\Lambda,\Sigma$, and $N=n,p$, can be used to determine the parity of the kaon. We would like to stress that in this work, speaking about the parity of kaon, we mean the relative (not absolute) *P* parity with respect to that of the

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$\Lambda p$ system. Due to the conservation of strangeness in strong and electromagnetic interactions, it is possible to determine only the relative (but not the absolute) parity of the kaons as in the case of $\pi^0$ and $\eta$ mesons.

Note that the processes $\vec{p}+\vec{p}\to K+Y+N$ is suitable for the determination of the parity of kaons with positive strangeness $(K^+,K^0)$, whereas the process $K^-+{}^4\mathrm{He}\to {}^4_\Lambda H+\pi^0$ is suitable for antikaons with negative strangeness. Therefore, these two processes are complemetary, and thus need to be studied independently for additional testing of the validity of $C$ and $CPT$ invariances of fundamental interactions.

Our argument will be based on the property that the production of strange particles near threshold is dominantly of $S$-wave nature [9]. That is, $l_1=l_2=0$, where $l_1$ is the orbital angular momentum of the $\Lambda N$ system, and $l_2$ is the orbital angular momentum of kaon (relative to the center of mass of the $\Lambda N$ system).

In the pseudoscalar case, only two transitions are allowed for the processes $\vec{p}+\vec{p}\to K+N+Y$ (with $Y=\Lambda,\Sigma$), namely,

$$S_i=1,\ l=1\to\ J^P=0^-,\quad S_i=1,\ l=1\to\ J^P=1^-, \tag{1}$$

where $S_i(l)$ is the total spin (orbital angular momentum) of colliding protons and $J^P$ is the total angular momentum ($J$) and the parity of the corresponding channel. Note that both transitions are triplet ones. Therefore, the dependence of the differential cross section on the polarizations $\vec{P}_1$ and $\vec{P}_2$ of protons (in the initial state) must be given by the following expression:

$$\frac{d\sigma^{(-)}}{d\omega}(\vec{P}_1,\vec{P}_2)=\frac{\sigma_{1,0}}{4}[1+\vec{P}_1\cdot\vec{P}_2-2(\vec{k}\cdot\vec{P}_1)(\vec{k}\cdot\vec{P}_2)]+\frac{\sigma_{1,1}}{2}[1+(\vec{k}\cdot\vec{P}_1)(\vec{k}\cdot\vec{P}_2)] \tag{2}$$

where $\vec{k}$ is the unit vector along the three-momentum of proton beam $\sigma_{1,0}$ and $\sigma_{1,1}$ are the cross sections in the triplet $pp$ state (with two possible values of the projection of the total spin of initial protons, namely, $m_s=0$ and $m_s=\pm 1$, respectively) $d\omega$ is the element of the phase space of the final particles, and the upper index $(-)$ indicates that kaon is pseudoscalar.

Then, the spin correlation coefficients $A_i$ which are defined via

$$\frac{d\sigma^{(-)}}{d\omega}(\vec{P}_1,\vec{P}_2)=\left(\frac{d\sigma}{d\omega}\right)_0[1+A_1^{(-)}(\vec{P}_1\cdot\vec{P}_2)+A_2^{(-)}(\vec{k}\cdot\vec{P}_1)\times(\vec{k}\cdot\vec{P}_2)], \tag{3}$$

where $(d\sigma/d\omega)_0$ is the differential cross section of unpolarized proton collisions, can be expressed in terms of $\sigma_{1,0}$ and $\sigma_{1,1}$ as

$$A_1^{(-)}=\frac{\sigma_{1,0}}{\sigma_{1,0}+2\sigma_{1,1}},\quad A_2^{(-)}=2\frac{\sigma_{1,0}-\sigma_{1,1}}{\sigma_{1,0}+2\sigma_{1,1}},$$

$$(d\sigma/d\omega)_0=\tfrac{1}{4}(\sigma_{1,0}+2\sigma_{1,1}). \tag{4}$$

Independently of the model used for the calculation of the cross sections $\sigma_{1,0}$ and $\sigma_{1,1}$, one can obtain the following general relations for $A_i^{(-)}$:

$$A_1^{(-)}\geqslant 0,\quad -1\leqslant A_2^{(-)}\leqslant 2,\quad 3A_1^{(-)}+A_2^{(-)}=1. \tag{5}$$

The cross sections $\sigma_{1,0},\sigma_{1,1}$ are determined by the partial amplitudes which correspond to the transitions (1), with the following spin structures:

$$f_0(\xi_4^+\sigma_2\tilde{\xi}_3^+)[\tilde{\xi}_2\sigma_2(\vec{\sigma}\cdot\vec{k})\xi_1], \tag{6}$$

$$if_1(\xi_4^+\sigma_a\sigma_2\tilde{\xi}_3^+)[\tilde{\xi}_2\sigma_2(\vec{\sigma}\times\vec{k})_a\xi_1],$$

where $f_0$ and $f_1$ are the amplitudes, corresponding to the transitions with $J^P=0^-$ and $J^P=1^-$, respectively, and $\xi_1$ and $\xi_2(\xi_3$ and $\xi_4)$ are the two-component spinors of the initial protons (final $N$ and $Y$).

Using Eq. (6), the following expressions can be obtained for the cross sections $\sigma_{1,0}$ and $\sigma_{1,1}$:

$$\sigma_{1,0}=4|f_0|^2,\quad \sigma_{1,1}=8|f_1|^2. \tag{7}$$

For the scalar kaon, near threshold strange particle production is characterized by a single transition, namely,

$$S_i=0,\quad l=0\to J^P=0^+. \tag{8}$$

So, for the dependence of the differential cross section on the polarizations of the colliding protons, we can write the following expression:

$$(d\sigma^{(+)}/d\omega)(\vec{P}_1,\vec{P}_2)=\tfrac{1}{4}\sigma_s(1-\vec{P}_1\cdot\vec{P}_2), \tag{9}$$

i.e.,

$$A_1^{(+)}=-1,\quad A_2^{(+)}=0, \tag{10}$$

where $\sigma_s$ is the cross section in the singlet state. The corresponding spin structure of the matrix element is determined by the expression

$$f_0^{(+)}(\xi_4^+\sigma_2\tilde{\xi}_3^+)(\tilde{\xi}_2\sigma_2\xi_1). \tag{11}$$

We get from Eq. (11)

$$\sigma_s=4|f_0^+|^2. \tag{12}$$

Comparing Eqs. (4) and (10), one can see that, the sign of the spin correlation coefficient $A_1$ is determined uniquely by the value of the kaon parity. It is important to note that, such a sign correlation for $A_1$ and $\mathcal{P}_K$ has a universal nature, as we do not use any model for the calculation of the threshold amplitudes. Instead, we used here only the general symmetry properties of strong interactions, such as the parity invariance, and the Pauli principle for the identical protons. Our dynamical assumption, concerning the $S$-wave nature of the final three-particle state, is also of a general character, and is based on the short range nature of strong interactions.

Next, we will present another experimental method for the determination of the $P$ parity of kaon. Let us first note that, another polarization observable, which can be nonzero near the reaction threshold, and also sensitive to the parity of kaons, is the polarization transfer from initial proton to the final hyperon which is called the spin transfer coefficient. Measurements of such correlations are planned in the experiment of DISTO Collaboration [10–12], at LNS, for a proton energy 2.9 GeV, i.e., in the near-threshold region.

For the $S$-wave production of strange particles, the dependence of the $Y$ polarization $\vec{P}_Y$ on the polarization of proton beam can be represented by the following expression:

$$\vec{P}_Y = p_1 \vec{P} + p_2 \vec{k}(\vec{k}\cdot\vec{P}), \tag{13}$$

where $\vec{P}$ is the polarization of one of the initial protons. The polarization structure functions $p_1$ and $p_2$ determine the polarization transfer coefficients, namely,

$$K_x^{x'} = K_y^{y'} = p_1, \quad K_z^{z'} = p_1 + p_2 \tag{14}$$

if the $z$ axis is chosen along the three-vector $\vec{k}$.

For the pseudoscalar kaons, $p_1$ and $p_2$ are determined by the following expressions:

$$p_1^{(-)} = \frac{2\,\mathrm{Re}(f_0 f_1^*)}{|f_0|^2 + 2|f_1|^2},$$

$$p_2^{(-)} = \frac{-|f_1|^2 - 2\,\mathrm{Re}(f_0 f_1^*)}{|f_0|^2 + 2|f_1|^2}. \tag{15}$$

But for the scalar kaons, both of these structure functions are zero, $p_1^{(+)} = p_2^{(+)} = 0$, in the entire kinematical threshold region, because only singlet-singlet transition is allowed in this case. Therefore any nonzero value for $p_1$, must be a signature for the pseudoscalar nature for the $K$ meson.

It is worth discussing what to do, if one gets $p_1^{(-)} = 0$, that is,

$$\mathrm{Re}(f_0 f_1^*) = 0, \tag{16}$$

for some unknown reason, imitating the scalar case. It is clear that such a condition, in the entire kinematical region for near threshold strange particle production process, could appear only accidentally. Let us analyze next how this condition can be tested experimentally. We will use the following solutions of Eq. (16):

$$\text{(a)} \quad |f_0| = 0, \quad |f_1| \neq 0, \tag{17}$$

$$\text{(b)} \quad |f_1| = 0, \quad |f_0| \neq 0,$$

$$\text{(c)} \quad \delta_0 - \delta_1 = \frac{\pi}{2}, \quad |f_0| \neq 0, \quad |f_1| \neq 0,$$

where $\delta_0$ and $\delta_1$ are the phases of the complex amplitudes $f_0$ and $f_1$.

The first two solutions lead to the following predictions for the spin-correlation coefficients:

$$\text{(a)} \quad A_1 = 0, \quad A_2 = 1, \tag{18}$$

$$\text{(b)} \quad A_1 = 1, \quad A_2 = -2.$$

The third solution in Eq. (17) corresponds to maximum possible values for the following $T$-odd polarization observables:

$$\vec{P}_1 \times \vec{P}_2 \cdot \vec{P}_Y, \quad (\vec{k}\cdot\vec{P}_1 \times \vec{P}_2)(\vec{k}\cdot\vec{P}_Y),$$
$$(\vec{k}\cdot\vec{P}_1 \times \vec{P}_Y)(\vec{k}\cdot\vec{P}_2), \quad (\vec{k}\cdot\vec{P}_2 \times \vec{P}_Y)(\vec{k}\cdot\vec{P}_1), \tag{19}$$

which can be determined by a single parameter $\mathrm{Im}(f_0 f_1^*)$. This completes our discussion on how to distinguish experimentally between the different conditions (17) which lead to the accidental result (16).

Finally, we would like to elaborate on our basic assumption concerning the $S$-wave nature of the near threshold production of strange particles. The main problem for the determination of the kaon parity in both methods we have proposed, is the possible contribution of the $P$ wave for the final state particles, which, in principle, can destroy the definite correlation between the signs of $A_1$ and $\mathcal{P}_K$, predicted for the $S$-wave production.

To estimate how serious this contribution is, let us first analyze the effects which can lead to $P$-wave production. For the pseudoscalar case, the $P$-wave excitation ($l_1 = 1, l_2 = 0$, or $l_1 = 0, l_2 = 1$) can only come from the singlet states

$$S_i = 0, \quad l = 0 \to J^p = 0^+ (S_f = 1, l_1 = 1), \tag{20}$$

$$S_i = 0, \quad l = 2 \to J^p = 1^+ (S_f = 1, l_1 = 1).$$

Let us first note that the general structure in Eq. (3) of the cross section is valid in this case as well. Then, taking into account the triplet ($S$ state of $KNY$ system) and singlet ($P$ state of KNY system) transitions, the following expressions can be obtained for $A_1$ and $A_2$:

$$A_1 = \frac{\sigma_{1,0} - \sigma_s}{\sigma_{1,0} + 2\sigma_{1,1} + \sigma_s}, \quad A_2 = \frac{2(\sigma_{1,1} - \sigma_{1,0})}{\sigma_{1,0} + 2\sigma_{1,1} + \sigma_s}, \tag{21}$$

where $\sigma_s$ is determined by $P$-wave contributions only. One can see that these $P$-wave contributions lowers the value of $A_1$ and, in principle, can imitate the scalar case for which $A_1 = -1$, in the pseudoscalar case. But this is possible only in the limit $\sigma_{1,0} = \sigma_{1,1} = 0$, where $S$-wave strange particle production is absent. In the general case, the negative values of $A_1$ are possible only for $\sigma_s = \sigma_{1,0}$. This, however, is known to be very unlikely for the production of strange particles near the threshold.

Next we will present some general qualitative arguments to support our conjecture that the near-threshold region with $S$-wave production of strange particles, is sufficiently broad. To prove this claim, let us estimate the ''strange radius'' $R_s$ of the proton as the size of the region inside the proton which can effectively generate the strange particles (in $\pi N$ or $NN$

collisions). Let us first note that a virtual transition $N \to KY$ can be relalized with an energy deficit $\Delta E \geqslant m_K$. This leads to $R_s \leqslant 1/m_K$. Then, following the quasiclassical reasoning, the orbital angular momentum of the kaon or $Y$ hyperon produced from such a region, must be $l \leqslant p^*/m_K$ where $p^*$ is the corresponding momentum in the c.m. system (c.m.s.).

The size of the $S$-wave region could also be determined experimentally, independent of the arguments which we have presented above. For this aim, it is necessary to find manifestations of the angular anisotropy of the produced particles. Luckily, there exist processes with broad $S$-wave regions, namely, $\pi^- p \to n\omega$ [13–15], and $d + p \to {}^3\mathrm{He} + \omega$ [16] with angular isotropy up to $p^* \approx 200$ MeV/$c$.

In addition to the angular anisotropy, there exist other observables, which can characterize the possible contribution of the $P$ wave, namely, the single-spin polarization effects. Single-spin polarization observables, such as the polarization of $\Lambda$ produced in collisions of unpolarized nucleons, or the analyzing power $\mathcal{A}$, which is a result of polarization of the colliding protons, can be very sensitive to the $P$-wave contributions, as they are exactly zero in the case of the $S$-wave production.

To determine the sign of $A_1$ (and thus to establish the $P$ parity of kaons), it is necessary to reverse the direction of the beam polarization. Here, detection of all the produced particles is unnecessary; it is enough to detect only the kaon. To increase the experimental statistics, one can measure the inclusive cross sections such as $\vec{p}(\vec{p},K^+)YN$ or $\vec{p}(\vec{p},\Lambda)KN$, or even the asymmetry of the total cross section. This compensates the decrease in the cross section in the near-threshold region (due to the decrease of the phase space volume of the produced particles).

If we summarize, the new methods suggested for the experimental determination of the $P$ parity of kaons, which are based on the measurement of the sign of the spin correlation coefficient $A_1$, and the polarization transfer coefficient in the near-threshold production of strange particles, are very general. They were based on a simple and model-independent dynamics; namely, we only used the parity invariance of the strong interactions, and the $S$-wave nature of strange particle production near threshold. Using some simple qualitative arguments, we have demonstrated that this near-threshold region must be broad enough, whose size is defined by the strange radius of the proton, namely, by the size of the region inside the proton which can generate the strange particles. These new methods for measuring the parity of kaon can be tested in LNS (Saclay), COSY (Germany), KEK (Japan), and JINR (Dubna).

Recently, the DISTO Collaboration published results [17] about the polarization phenomena in $pp \to \Lambda K^+ p$, namely, the analyzing power $\mathcal{A}_y$ induced by polarized proton beam, polarization $P_\Lambda$ of the $\Lambda$ hyperon, and the polarization transfer coefficient $D_{NN}$. Their most interesting result for our work, is the nonvanishing value for the polarization transfer coefficient $D_{NN}$, which was measured at proton momentum 3.67 GeV/$c$. This result confirms our prediction that the $P$ parity of the $K^+$ meson is negative. We do not consider this result as the ultimate proof of the pseudoscalar nature of $K^+$ meson, however, as the proton momentum where the measurement is carried is quite far from the reaction threshold value. Furthermore, the nonzero values (although small) of $P_\Lambda$ and $\mathcal{A}_y$ signal the presence of some non-$s$-wave contributions. For the final solution of this problem, it would be good to repeat the measurements of the polarization characteristics at 2.94 GeV/$c$, the smallest momentum for DISTO. The latest results of COSY [18] concerning the energy dependence of the total cross section for the process $pp \to \Lambda K^+ p$ demonstrate that this process can be detected very near the threshold, for the small values of the excitation energy less than 10 MeV.

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