Determination of the parity of the pentaquark baryons: \( \Theta^+ \) and \( \Xi_5 \)

Seung-Il Nam,\(^{1,2} \) Atsushi Hosaka,\(^{1} \) and Hyun-Chul Kim\(^{2} \)

\(^{1}\)Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan
\(^{2}\)Department of Physics and Nuclear Physics & Radiation Technology Institute (NuRI), Pusan University, Keum-jung gu, Busan 609-735, Korea

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Abstract

We study determination of the parity of the pentaquark baryons in two different processes. First, we investigate the \( \Theta^+ \) production via the \( \vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+ \) reaction process which was proposed to determine unambiguously the parity of \( \Theta^+ \). We observe the clear differences in the total cross sections and the spin observable \( A_{xx} \). As for the \( \Xi_5 \) in the \( \bar{K}N \rightarrow K\Xi_5 \) reaction process, the total cross section for the positive parity presents about one hundred times larger than that of the negative one due to the huge destructive interference.

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\(^{*}\)Electronic address: sinam@rcnp.osaka-u.ac.jp
\(^{†}\)Electronic address: hosaka@rcnp.osaka-u.ac.jp
\(^{‡}\)Electronic address: hchkim@pusan.ac.kr
I. INTRODUCTION

The observation of the evidence of $\Theta^+$ by LEPS collaboration \cite{1} motivated by Diakonov et al. \cite{2} has intrigued huge amount of the research activities on hadron physics. Though the quite interesting features of the pentaquark baryons have been revealed from the experimental and theoretical approaches so far, we still have many unknown properties of the baryons which have not been settled yet. In this report, we study the reaction dynamics to determine one of the unknowns, the parity of the baryons. As being introduced by Thomas et al. \cite{3}, we consider the spin statistics of the reaction observable in the $\vec{p}\vec{p} \rightarrow \Sigma^+ \Theta^+$ process which will shed the light on the determination of the parity of $\Theta^+$ without model dependence. We observe clear difference in the size and energy dependence of the total cross sections depending on the parity of $\Theta^+$. We also find the huge destructive interference for the negative parity $\Xi^+_5$ production from the $\bar{K}N \rightarrow K \Xi^+_5$ process. The interference provides about one hundred times smaller total cross section for the negative parity $\Xi^+_5$ than that of the positive one. This report is organized as follows. In the second section we will present the results of the $\vec{p}\vec{p} \rightarrow \Sigma^+ \Theta^+$ process. The next section will be given for the $\Xi^+_5$ production from the $\bar{K}N \rightarrow K \Xi^+_5$ process. The final section is devoted to summary and conclusions.

II. THE $\vec{p}\vec{p} \rightarrow \Sigma^+ \Theta^+$ PROCESS

In this section, we consider the $\vec{p}\vec{p} \rightarrow \Sigma^+ \Theta^+$ process \cite{4}. This reaction process will provide the unambiguous method to determine the parity of $\Theta^+$ with the Pauli principle and the relation of the parity $P = (-1)^L$ due to the following reason. If the initial spin state is $S = 0$, the final state will be dominated by the production of the positive parity $\Theta^+$ with even $L$. Otherwise, the negative parity $\Theta^+$ will be produced when the initial spin state is $S = 1$ with odd $L$. In this way, this method can be addressed as a model independent method for the determination of the parity of $\Theta^+$.

Now, we perform the Born approximation calculation with the inclusion of the phenomenological form-factor of dipole type. We assumed one condition that the final state is dominated by the $S$–wave for the validity of the method. We have confirmed this by looking at the angular distribution for the positive and negative parity $\Theta^+$ as shown in the upper panels of Fig.\ref{fig:fig1}. The curves are plotted for the several center of mass (CM) energies, $\sqrt{s} = 2730 \sim 2760$ MeV. Near the threshold region, the angular distributions for the two parities are dominated by $S$–wave contributions. Therefore, one can confirm that the condition for the model independent method will be successfully valid for the low energy region whereas the higher partial wave contributions are mixed as the CM energy grows.

In the lower panels of Fig.\ref{fig:fig1}, we show the total cross sections for the allowed and forbidden channels. We observe the obvious differences in the order of magnitudes. For the allowed channel, we also show the results with the different sign combinations of the $K*NN\Theta^+$ coupling constants which can not be determined by SU(3) symmetry. As for the forbidden channel, we show only the case without the $K*NN\Theta^+$ coupling. The parameter dependence seems not so significant. We also note that the threshold behavior for the allowed channel shows $S$–wave type $(\sigma \sim (s-s_{th})^{1/2})$ whereas $P$–wave $(\sigma \sim (s-s_{th})^{3/2})$ for the forbidden channel. These quite different threshold behavior will be critical information when polarized proton scattering experiments tell the parity of $\Theta^+$. 

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Hanhardt et al. proposed the spin observable $A_{xx}$ which is defined by the following,

$$A_{xx} = \frac{(3\sigma_0 + 3\sigma_1)}{2\sigma_0} - 1. \quad (1)$$

As discussed in Ref. [5], this quantity showed clear separation of the parities. In the upper panels of Fig. 2 we present the $A_{xx}$ for the two parities of $\Theta^+$. As for the positive parity, all curves almost lie in the negative region and vice versa for the negative parity $\Theta^+$. This tendency agrees well with the results of Ref. [5]. Furthermore, this quantity has an advantage that the effects caused by the form-factor and unknown parameters will be reduced since the effects of them appear both in the denominator and in the numerator at the same time in Eq. (1), though the cancellation is not perfect. We note that the spin observable $A_{xx}$ is quite promising to determine the parity of $\Theta^+$ with less model dependence.

III. THE $\bar{K}N \rightarrow K\Xi_5$ PROCESS

NA49 collaboration reported that another pentaquark baryon $\Xi_5(S = -2, T = 3/2)$ with a mass $\sim 1860$ MeV. Though the observation must be confirmed more carefully, here, we consider the production of the baryon in the $\bar{K}N \rightarrow K\Xi_5$ reaction process in a simple Born diagram calculation. It is worth mentioning that there is no $t$-channel contribution since it is impossible to change the strangeness by two units by an exchange of a known meson. The $K\Sigma\Xi_5$ coupling constant is taken from the relation shown in Ref. [7] with $\Gamma_{\Theta^+ \rightarrow KN} = 15$ MeV. We only consider the $\bar{K}^0 p \rightarrow K^0 \Xi_5^-$ isospin channel since the difference due to other
FIG. 2: Upper panels: $A_{XX}$ for the positive (left panel) and negative (right panel) parities of $\Theta^+$. Lower panels: Total cross sections of the $\bar{K}N \rightarrow K^{0}\Xi_5$ process for the positive parity $\Xi_5$ (left panel) and the negative one (right panel).

isospin channel is small. In the lower panels of Fig. 2, we show the total cross sections for the process with the two parities of $\Xi_5$. In order to check the model dependence, we consider two different types of the form-factors, $F_1$ and $F_2$. Though we observe quite sizable model dependence from the form-factors, we would like to emphasize that huge difference in the order of the magnitudes for the two parities which is about factor one hundred. This result is an interesting feature of the $\Xi_5$ production which will be helpful to give a qualitative determination for the parity if experimental data will be available.

IV. SUMMARY AND CONCLUSIONS

We performed calculations for the two pentaquark production processes, $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$ and $\bar{K}N \rightarrow K\Xi_5$ by using the Born approximation. The main purpose for these calculations was to provide reliable methods and information to determine the parities of the two pentaquark baryons. We also considered model dependence of the cross sections through unknown coupling constants and form-factors. We found quite useful information to determine the parity of $\Theta^+$ in the polarized proton scattering. Since this reaction is less model dependent, the results of this work is quite promising for the determination in future experiments. Also, the interesting feature in the $\Xi_5$ production reaction process can be a good milestone at the first stage of the analysis in experiments. As planned by the COSY-TOF collaboration, the polarized proton scattering will be done in near future with our expectation for the
determination of the parity of $\Theta^+$. 

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