Production of the Pentaquark Exotic Baryon $\Xi_{5}$ in $\bar{K}N$ Scattering:

$\bar{K}N \to K\Xi_{5}$ and $\bar{K}N \to K^{*}\Xi_{5}$

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We investigate the production of the newly found pentasquark exotic baryon $\Xi_{5}$ in the $\bar{K}N \to K\Xi_{5}$ and the $\bar{K}N \to K^{*}\Xi_{5}$ reactions at the tree level. We consider both positive- and negative-parities of the $\Xi_{5}$. The reactions are dominated by the s- and the u-channel processes, and the resulting cross sections are observed to depend very much on the parity of $\Xi_{5}$ and on the type of form factor. We have seen that the cross sections for the positive-parity $\Xi_{5}$ are generally about a hundred times larger than those of the negative-parity one. This large difference in the cross sections will be useful for further study of the pentaquark baryons.

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I. INTRODUCTION

The experimental observation of the $\Theta^{+}$ performed by the LEPS collaboration at SPring-8 [1], which is motivated by Diakonov et al. [2], has paved the way for intensive studies on the exotic five-quark baryon states, also known as pentaquarks, experimentally [3] as well as theoretically [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. As a consequence of the finding of the $\Theta^{+}$, the existence of other pentaquark baryons, such as the $\Lambda_{5}$, $\Sigma_{5}$, and $\Xi_{5}$, which have also been predicted theoretically, is anticipated.

The NA49 [31] collaboration reported a signal for the pentaquark baryon $\Xi_{5}$, which was also predicted theoretically. The $\Xi_{5}$ was found to have a mass of 1862 MeV, a strangeness $S = -2$, and an isospin $I = 3/2$. It is characterized by its narrow decay width of $\sim 18$ MeV, like that of the $\Theta^{+}$. However, we have thus far no concrete experimental evidence for its quantum numbers such as spin and parity.

As for the parity of the $\Theta^{+}$, a consensus has not been reached. For example, the chiral soliton model [2, 3], the diquark model [3], the chiral potential model [8], and constituent quark models with spin-flavor interactions [10, 11, 12] prefer a positive-parity for the $\Theta^{+}$ whereas the QCD sum rule approach [7, 8] and the quenched lattice QCD [13, 14] have supported a negative-parity. In the meanwhile, various reactions for $\Theta^{+}$ production [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30] have been investigated, where the determination of the parity of $\Theta^{+}$ has been emphasized. In many cases, the total cross-sections of the positive-parity $\Theta^{+}$ production is typically about ten times larger than those of the negative-parity one. Liu et al. [32] evaluated the $\gamma N \to K\Xi_{5}$ reactions, assuming the positive-parity $\Xi_{5}$ and its spin $J = 1/2$. However, since the parity of the $\Xi_{5}$ is not known yet, it is worthwhile studying the dynamics of $\Xi_{5}$ production with two different parities taken into account.

However, we note that negative results for the pentaquark baryons have emerged recently. Especially, the CLAS collaboration at Jefferson laboratory could not see any obvious evidence for the $\Theta^{+}$ pentaquark, which was expected to have a peak at about $1530 \sim 1540$ MeV in the reaction $\gamma p \to \bar{K}^{0}\Theta^{+}$ [33]. Moreover, the existence of an $S = -2$ pentaquark, such as the $\Xi_{5}$ or the charmed pentaquark ($\Theta_c^+$), has not been confirmed yet.

In the present work, nonetheless, for the unclear status of the pentaquark, we want to investigate the $\Xi_{5}$ production from the $\bar{K}N \to K\Xi_{5}$ and the $\bar{K}N \to K^{*}\Xi_{5}$ reactions. Due to the exotic strangeness quantum number the $\Xi_{5}$ has, the reaction process at the tree level becomes considerably simplified. This is a very specific feature of the process.

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1 Recently, Ref. [4] pointed out that the exclusion of the non-interacting $K\bar{N}$ state from the two-point correlation function may reverse the parity of $\Theta^{+}$. 
As discussed in Ref. [34], we do not include the \( B \) for the production of \( \Xi^5 \) for the reactions by \( \bar{\Sigma}^+ p \rightarrow K^+ \Xi^5 \). We assume that the spin of the \( \Xi^5 \) is 1/2 [32]. Then, we estimate the total and the differential cross-sections for the production of \( \Xi^5 \) with positive and negative parities.

This paper is organized as follows: In Section II, we define the effective Lagrangians and construct the invariant amplitudes. In Section III, we present the numerical results for the total and the differential cross-sections for both positive- and negative-parity \( \Xi^5 \). Finally, in Section IV, we briefly summarize our discussions.

\section{II. EFFECTIVE LAGRANGIANS AND AMPLITUDES}

We study the reactions \( \bar{K}N \rightarrow K\Xi^5 \) and \( \bar{K}N \rightarrow K^*\Xi^5 \) by using an effective Lagrangian at the tree level of Born diagrams. The reactions are schematically presented in Fig. 1 where we define the four momenta of each particle for the reactions by \( p_1,\ldots,4 \). There is no \( t \)-channel contribution because strangeness-two (\( S=2 \)) mesons do not exist. As discussed in Ref. [34], we do not include the \( B_{\bar{g}g}B_{\bar{g}g} \) coupling because it is forbidden in exact SU(3) flavor symmetry. Hence, the interaction Lagrangians can be written as

\[
\mathcal{L}_{K\Sigma\Xi^5} = ig_{K\Sigma\Xi^5}\bar{\Sigma}\gamma_5 KN + (h.c.),
\]

\[
\mathcal{L}_{K\Sigma\Xi^5} = ig_{K\Sigma\Xi^5}\bar{\Sigma}\gamma_5 KN + (h.c.),
\]

\[
\mathcal{L}_{K^*\Sigma\Xi^5} = g_{K^*\Sigma\Xi^5}\gamma_\mu K^*\mu N + (h.c.),
\]

\[
\mathcal{L}_{K^*\Sigma\Xi^5} = g_{K^*\Sigma\Xi^5}\bar{\Sigma}\gamma_5 K^*\mu N + (h.c.),
\]

where \( \Sigma, \Xi^5, N, K, \) and \( K^* \) denote the corresponding fields for the octet \( \Sigma \), the antidecuplet \( \Xi^5 \), the nucleon, the pseudo-scalar \( K \), and the vector \( K^* \), respectively. The isospin operators are dropped because we treat the isospin states of the fields explicitly. We define \( \Gamma_5 = \gamma_5 \) for the positive-parity \( \Xi^5 \) whereas \( \Gamma_5 = 1_{4\times4} \) for the negative-parity one. \( \Gamma_5 \) is also defined by \( \Gamma_5 \gamma_5 \) for the vector meson \( K^* \). The values of the coupling constants \( g_{K\Sigma\Xi^5} \) and \( g_{K^*\Sigma\Xi^5} \) are taken from the new Nijmegen potential [35] as \( g_{K\Sigma\Xi^5} = 3.54 \) and \( g_{K^*\Sigma\Xi^5} = -2.99 \) whereas we assume SU(3) flavor symmetry for \( g_{K\Sigma\Xi^5} \) so that we obtain the relation \( g_{K\Sigma\Xi^5} = g_{K\Sigma\Xi^5} \). Employing the decay width \( g_{K\Sigma\Xi^5} \), we obtain \( g_{K\Sigma\Xi^5} = g_{K\Sigma\Xi^5} = 3.77 (0.53) \) for the positive (negative) parity. The remaining one, \( g_{K\Sigma\Xi^5} \), is not known, which we will discuss in the next section.

The invariant scattering amplitude for \( \bar{K}N \rightarrow K\Xi^5 \) can be written as

\[
i\mathcal{M}_{x,K} = ig_{K\Sigma\Xi^5}g_{K\Sigma\Xi^5}F_x^2(q^2)\bar{u}(p_4)\Gamma_5\frac{p_x + M_{\Sigma}}{q_x^2 - M_{\Sigma}^2}\gamma_5 u(p_2),
\]

where \( x \) labels either the \( s \)-channel or the \( u \)-channel, and the corresponding momenta are \( q_x = p_1 + p_2 \) and \( q_u = p_2 - p_3 \). For \( \bar{K}N \rightarrow K^*\Xi^5 \), we have

\[
i\mathcal{M}_{x,K^*} = g_{K^*\Sigma\Xi^5}g_{K^*\Sigma\Xi^5}F_x^2(q^2)\bar{u}(p_4)\Gamma_5\frac{p_x + M_{\Sigma}}{q_x^2 - M_{\Sigma}^2}u(p_2),
\]

\[
i\mathcal{M}_{u,K^*} = g_{K^*\Sigma\Xi^5}g_{K^*\Sigma\Xi^5}F_u^2(q^2)\bar{u}(p_4)\Gamma_5\frac{p_u + M_{\Sigma}}{q_u^2 - M_{\Sigma}^2}u(p_2).
\]

As indicated in Eq. [2], the coupling constants are commonly factored out for the \( s \)- and the \( u \)-channels in the \( K \) production. Therefore, there is no ambiguity due to the sign of the coupling constants. On the contrary, there is such an ambiguity due to the unknown sign of \( g_{K^*\Sigma\Xi^5} \) in the case of \( K^* \) production.

Since the baryon has an extended structure, we need to introduce a form factor. We employ the form factor [20]

\[
F_1(x) = \frac{\Lambda_1^2}{\sqrt{\Lambda_1^2 + (x - M_{\Xi^5}^2)^2}}
\]
FIG. 2: Energy dependence of the squared form factors $F_1^2(s)$, $F_2^2(u)$ and the $F_2^2(q^2)$ (a), and angular dependence of the squared form factor $F_1^2$ for the $s$- and the $u$-channels at three CM energies. The types of curves are explained by the labels in the figure.

in such a way that the singularities appearing in the pole diagrams can be avoided. Here, $\Lambda_1$ and $M_\Sigma$ stand for the cutoff parameter and the $\Sigma$ mass, respectively. We set the cutoff parameter $\Lambda_1 = 0.85$ GeV as in Ref. \[24\]. This value was used to reproduce the cross sections of $\gamma p \rightarrow K^+\Lambda$. In order to verify the dependence of the form factor, we consider also the three-dimensional form factor

$$F_2(q^2) = \frac{\Lambda_2^2}{\Lambda_2^2 + |q^2|},$$

where $\vec{q}$ denotes the three momentum of the external meson. As for the cutoff parameter, we set $\Lambda_2 = 0.5$ GeV, which was deduced from the $\pi N \rightarrow K\Lambda$ reaction \[15\].

In the left panel (a) of Fig. 2 we show the dependence of the two form factors $F_1$ and $F_2$ on the CM energy while in the left panel (b) the angular dependence of the $F_1$ form factor is drawn. The $F_2$ form factor does not have any angular dependence. Obviously, they show very different behaviors. For instance, the $F_2$ decreases much faster than $F_1$ as the center-of-mass (CM) energy grows. The form factor $F_1$ in the $u$-channel shows a strong enhancement in a backward direction as the CM energy increases. As we will see, this feature has a great effect on the angular dependence of the differential cross-sections.

III. NUMERICAL RESULTS

A. $\bar{K}N \rightarrow K\Xi_5$

In this subsection, we discuss the results for the reaction $\bar{K}N \rightarrow K\Xi_5$. Due to isospin symmetry, we can verify that the two possible reactions $\bar{K}^0p \rightarrow K^0\Xi_5^+$ and $K^-n \rightarrow K^+\Xi_5^-$ are exactly the same in the isospin limit. In Fig. 3 we present the total and the differential cross-sections in the left and the right panels, respectively. The average values of the total cross-sections are $\sigma \sim 2.6 \mu b$ with the $F_1$ form factor and $\sigma \sim 1.5 \mu b$ with the $F_2$ in the energy range $E_{CM}^{th} = 2.35$ GeV $\leq E_{CM} \leq 3.35$ GeV (from the threshold to the point of 1 GeV larger). Though the average total cross-sections for the different form factors are similar in order of magnitude, the energy and the angular dependences are very different from each other. They are largely dictated by the form factor, as shown in Fig. 2. The angular distributions are drawn in the right panel (b) of Fig. 3 where $\theta$ represents the scattering angle between the incident and the final kaons in the CM system. We show the results at $E_{CM} = 2.4$, 2.6, and 2.8 GeV. As shown there, when $F_1$ is used, the backward production is strongly enhanced while the cross sections are almost flat apart from a tiny increase in the backward region, when $F_2$ is employed. Note that the angular dependence of the latter is the same as that of the bare cross section without the form factor.

In Fig. 4, we plot the total and differential cross-sections for the negative-parity $\Xi_5$. The energy dependence of the total cross section looks similar to that for the positive-parity one. We find that $\sigma \sim 26 \mu b$ for $F_1$ and $\sim 12 \mu b$ for $F_2$ in average for the CM energy region $E_{CM}^{th} \leq E_{CM} \leq 3.35$ GeV. We see that the total cross-sections are...
FIG. 3: Cross sections for production of the positive parity $\Xi_5$ in the reaction $\bar{K}^0 p \rightarrow K^0 \Xi_5^+$. (a) The left panel shows the total cross-sections as functions of the center-of-mass energy $E_{CM}$. (b) The right panel shows the differential cross-sections as functions of the scattering angle $\theta$ for incident energies $E_{CM} = 2.4, 2.6, \text{and} 2.8 \text{ GeV}$. In both cases, results using the form factors $F_1$ and $F_2$ are shown as indicated by the labels in the figures.

FIG. 4: Cross sections for production of the negative parity $\Xi_5$ in the reaction $\bar{K}^0 p \rightarrow K^0 \Xi_5^-$. Notations are the same as in Fig. 3.

almost a hundred times smaller than that for the positive-parity $\Xi_5$. The difference between the results of the two parities is even more pronounced than in the previously investigated reactions, such as $\gamma N, K N$, and $N N$ scattering [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30], where typically the difference was about an order of ten. In the present reaction, the interference between the $s$- and the $u$-channels becomes important, in addition to the kinematical effect in the $p$-wave coupling for the positive-parity (but not in the $s$-wave for the negative-parity), which is proportional to $\vec{\sigma} \cdot \vec{q}$ and enhance the amplitude at high momentum transfers. In the case of the positive parity, the two terms which are kinematically enhanced are interfered constructively, while for the negative-parity $\Xi_5$, the relatively small amplitudes without the enhancement factor is done destructively. These two effects are simultaneously responsible for the large difference in the cross sections.

In the right panel (b) of Fig. 4, the angular distributions for the production of the negative-parity $\Xi_5$ are plotted. Here, the angular dependence changes significantly as compared with the positive-parity case. When the form factor $F_2$ is used, forward scattering significantly increases because the bare amplitude shows an enhancement in the forward direction. When using $F_1$, however, due to its strong enhancement in the backward direction, the cross sections get quite larger in the backward direction, except for those in the vicinity of the threshold, i.e., $E_{CM} \leq 2.45 \text{ GeV}$. 
reaction. However, when the form factors Eqs. (4) and (5), with appropriate parameters for the coupling strengths and the cutoff parameters. In the cross sections strongly depend on the choice of form factors. In fact, Fig. 3 shows that there is no ambiguity in the relative signs of coupling constants for the case of the tree level. On one hand, this fact simplifies the reaction mechanism and, hence, the computation. Furthermore, this choice allows for a factor of a hundred.

Similar discussions apply for this case as for the positive parity case, but the values of cross sections are reduced by about a factor of a hundred. Nevertheless, it would be useful to summarize the present result for the total cross-sections in different energy and angular dependence when using different form factors. At this moment, it is difficult theoretically to say which is better. Nevertheless, it would be useful to summarize the present result for the total cross-sections in different energy and angular dependence when using different form factors. At this moment, it is difficult theoretically to say which is better. Nevertheless, it would be useful to summarize the present result for the total cross-sections in different energy and angular dependence when using different form factors. At this moment, it is difficult theoretically to say which is better. Nevertheless, it would be useful to summarize the present result for the total cross-sections in different energy and angular dependence when using different form factors.

### IV. SUMMARY AND DISCUSSION

We have studied the production of the pentaquark exotic baryon $\Xi_5^*$ (mass = 1862 MeV, $I = 3/2$ $S = -2$, spin = 1/2 (assumed)) in the reactions $\bar{K}N \rightarrow K^0 \Xi_5^*$ and $\bar{K}N \rightarrow K^+ \Xi_5^-$. We have employed two different phenomenological form factors Eqs. (4) and (5), with appropriate parameters for the coupling strengths and the cutoff parameters. In the present reactions, since two units of strangeness are transferred, only $s$- and $u$- channel diagrams are allowed at the tree level. On one hand, this fact simplifies the reaction mechanism and, hence, the computation. Furthermore, there is no ambiguity in the relative signs of coupling constants for the case of $K^0$ production. On the other hand, the cross sections strongly depend on the choice of form factors. In fact, Fig. 5 and Fig. 6 show that we have found a rather different energy and angular dependence when using different form factors. At this moment, it is difficult theoretically to say which is better. Nevertheless, it would be useful to summarize the present result for the total cross-sections in different energy and angular dependence when using different form factors.
FIG. 6: Cross sections for production of the positive parity $\Xi_5$ in the reaction $\bar{K}^0 p \rightarrow K^* \Xi_5^+$ with the $F_2$ form factor employed. For notations, see the caption of Fig. 5.

FIG. 7: Cross sections for production of the negative parity $\Xi_5$ in the reaction $\bar{K}^0 p \rightarrow K^* \Xi_5^+$ with the $F_1$ form factor employed. The total cross-sections in (a) are calculated for four different $g_{K^*\Xi_5\Sigma}$ coupling constants as indicated by the labels. The angular distributions in (b) are calculated for three different CM energies and two different $g_{K^*\Xi_5\Sigma}$ coupling constants as indicated by the labels.

Table I. There, we see once again that the total cross-sections are, generally, much larger for positive-parity $\Xi_5$ than for positive-parity one by about factor of a hundred because there is a cancellation due to destructive interference.

| Reaction $\sigma_{\bar{K}N \rightarrow K\Xi_5}(P = \pm 1)$ | $F_1$ | $F_2$ | Reaction $\sigma_{\bar{K}N \rightarrow K^*\Xi_5}(P = \pm 1)$ | $F_1$ | $F_2$ |
|--------------------------------------------------|------|------|--------------------------------------------------|------|------|
| $\sigma_{\bar{K}N \rightarrow K\Xi_5}(P = +1)$ | 2.6 $\mu$b | 1.5 $\mu$b | $\sigma_{\bar{K}N \rightarrow K^*\Xi_5}(P = +1)$ | 1.6 $\mu$b | $\lesssim 2$ $\mu$b |
| $\sigma_{\bar{K}N \rightarrow K\Xi_5}(P = -1)$ | 26 nb | 12 nb | $\sigma_{\bar{K}N \rightarrow K^*\Xi_5}(P = -1)$ | 14 nb | $\lesssim 20$ nb |

TABLE I: Summary for the average total cross-sections in the CM energy region $2.35 \text{ GeV} \leq E_{\text{CM}} \leq 3.35 \text{ GeV}$ for $\bar{K}N \rightarrow K\Xi_5$ and $2.75 \text{ GeV} \leq E_{\text{CM}} \leq 3.75 \text{ GeV}$ for $\bar{K}N \rightarrow K^*\Xi_5$. For $K^*$ production with the $F_2$ form factor used, only the upper values are quoted because the interference suppresses them.
FIG. 8: Cross sections for production of the negative parity $\Xi_5$ in the reaction $\bar{K}^0 p \rightarrow K^{*0} \Xi_5^+$ with the $F_2$ form factor employed. For notations, see the caption of Fig. 7.

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