Production and parity determination of $\Xi$ baryons

Yongseok Oh · Kanzo Nakayama · Helmut Haberzettl

Received: date / Accepted: date

Abstract To understand the structure of hadrons and their production mechanisms, it is very important to be able to identify their quantum numbers. For investigating the spin and parity quantum numbers of $\Xi$ and $\Omega$ baryons, in particular, it is very important to understand strong interactions in the strangeness sector. At present, such quantum numbers are known for only a few of the $\Xi$ baryons, and even the parity of the ground state $\Xi(1318)$ has never been measured. In this article, we present a novel, model-independent way to determine the parity of $\Xi$ baryons solely based on symmetry considerations for the hadronic reaction $\bar KN \rightarrow K\Xi$.

1 Introduction

Regarding the production of strange baryons, the existing extensive studies on the production of $\Lambda$ and $\Sigma$ hyperons, which have strangeness $S = -1$, have accumulated many data for various physical quantities that are relevant for describing the production mechanisms of $S = -1$ baryons and the parameters of nucleon resonances. By contrast, the production of multi-strangeness $\Xi$ ($S = -2$) and $\Omega$ ($S = -3$) baryons has not been studied very often. One reason is that the processes for producing multi-strangeness baryons from non-strangeness initial states have very small cross sections. As a result, no significant information on multi-strangeness baryons has been added during the past two decades [1].

Recently, however, the interest in multi-strangeness physics is increasing. For example, the major research programs at J-PARC, which has started its operation re-
cently, include strangeness physics. Since the J-PARC facility can provide energetic kaon beams, the production of $\Xi(1318)$ should be possible. Furthermore, the PANDA Collaboration has a plan to investigate the $\bar{p}p \to \Xi \Xi$ reaction at FAIR, and the CLAS Collaboration at JLab has established the feasibility of investigating $\Xi$ spectroscopy via photoproduction reactions like $\gamma p \to K^+ K^+ \Xi^-$ and $\gamma p \to K^+ K^+ \pi^- \Xi^0$. The reported data for the total and differential cross sections as well as the $K^+ K^+$ and $K^+ \Xi^-$ invariant mass distributions for the $\gamma p \to K^+ K^+ \Xi^-$ reaction are the first data measured for the exclusive photoproduction of the $\Xi$. Recent theoretical investigations of this reaction can be found in Refs. [8,9].

The investigation of multi-strangeness baryons will shed light on our understanding of baryon structure by allowing us to distinguish various hadron models. (See, for example, Ref. [10] and references therein.) However, this requires knowledge of the quantum numbers of the baryons since the spin and parity quantum numbers heavily depend on the internal structure of the baryons and the underlying dynamics. It is of crucial importance, therefore, to identify the quantum numbers of the observed $\Xi$ baryons. However, identifying the spin and parity quantum numbers of multi-strangeness baryons is very challenging. For example, the fact that the $\Omega^-$ (1672) baryon has spin-3/2 was only recently confirmed by experiment [11], more than 40 years after the discovery of the $\Omega^-$ baryon [12]. For the cascade baryons, only for three states, $\Xi(1318)$, $\Xi(1530)$, and $\Xi(1820)$, of the eleven cascade states reported in PDG [1], the spin and parity quantum numbers are known. In a recent report [13], the BABAR Collaboration claimed that the $\Xi(1690)$ has $J^P = 1^+$. What is surprising is that the parity of the cascade ground state $\Xi(1318)$ has never actually been measured; the positive parity quoted by the PDG [1] is taken from quark-model calculations.

In this article, we describe a novel, model-independent way to determine the parity of spin-1/2 $\Xi$ baryons. To this end, we consider the reaction, $\bar{K}(q) + N(p) \to K(q') + \Xi[p']$, where the arguments $q, p, q'$, and $p'$ stand for the four-momenta of the respective particles. Although the production mechanisms are highly model-dependent [14,15], our method is based on Bohr’s theorem [16] and thus a direct consequence of the rotation and parity-inversion symmetries of the reaction amplitudes [17], and, therefore, model-independent. Furthermore, the cross section for this reaction is large enough to be measured experimentally.

2 Polarization observables and the parity of spin-1/2 $\Xi$ baryons

When the produced $\Xi$ has spin-1/2, the most general spin structure of the reaction amplitude constrained by symmetry principles for the reaction of $\bar{K}N \to K\Xi$ can be written as

$$\hat{M}^+ = M_0 + M_2 \sigma \cdot \hat{n}_2, \quad \hat{M}^- = M_1 \sigma \cdot \hat{n}_1 + M_3 \sigma \cdot \hat{q},$$

where $\hat{M}^+$ and $\hat{M}^-$, respectively, apply to $\Xi$ having positive or negative parity. The amplitude functions $M_i$ are functions of Mandelstam variables. The unit vectors $\hat{n}_1$ and $\hat{n}_2$ are defined as $\hat{n}_1 \equiv (q \times q')/(q \times q') \times q/|q \times q'|$ and $\hat{n}_2 \equiv q \times q'/|q \times q'|$, respectively. Without loss of generality, we may choose the coordinate systems such that $\hat{q}$ is the unit vector along the positive z-axis and $\hat{n}_2$ along the positive y-axis so
that $\hat{n}_1$ is the unit vector along the positive $x$-axis. The reaction plane is then defined by the two vectors $q$ and $\hat{n}_1$. This enables us to write the reaction amplitudes in a generic manner as

$$\hat{M} = \sum_{m=0}^{3} M_m \sigma_m,$$

(2)

where $\sigma_0$ is the $2 \times 2$ unit matrix. Depending on the parity of $\Xi$, either $M_1 = M_3 = 0$ or $M_0 = M_2 = 0$. The unpolarized cross section is then given by

$$\frac{d\sigma}{d\Omega} \equiv \frac{1}{2} \text{Tr} \left( \hat{M} \hat{M}^\dagger \right) = \sum_{m=0}^{3} |M_m|^2.$$

(3)

The most interesting spin observable related to the parity of the $\Xi$ is the (diagonal) spin-transfer coefficient $K_{ii}$ defined by

$$\frac{d\sigma}{d\Omega} K_{ii} \equiv \frac{1}{2} \text{Tr} \left( \hat{M} \sigma_i \hat{M}^\dagger \sigma_i \right) = |M_0|^2 + |M_i|^2 - \sum_{k \neq i} |M_k|^2,$$

(4)

for $i = 1, 2, 3$. In terms of the cross sections, this corresponds to

$$K_{ii} = \frac{|d\sigma_i(++) + d\sigma_i(--)| - |d\sigma_i(+) + d\sigma_i(-)|}{|d\sigma_i(++) + d\sigma_i(--)| + |d\sigma_i(+) + d\sigma_i(-)|},$$

(5)

where $d\sigma_i$ stands for the differential cross section with the polarization of the target nucleon and of the produced $\Xi$ along the $i$-direction. The first and second ± arguments of $d\sigma_i$ indicate the parallel (+) or anti-parallel (−) spin-alignment along the $i$-direction of the target nucleon and produced $\Xi$, respectively.

The spin-transfer coefficient $K_{ii}$ should be a function of the energy and scattering angle, in general. However, because of the spin structure of the amplitude, we can see that $K_{yy}$ is constant and

$$K_{yy} = \pi_\Xi,$$

(6)

where $\pi_\Xi$ is the parity of the produced $\Xi$. This is a direct consequence of the spin structures of the reaction amplitudes as exhibited in Eq. (1), which is a realization of reflection symmetry in the reaction plane. Therefore, the measurement of $K_{yy}$ will directly determine the parity of the $\Xi$.

Another way to determine the parity of spin-1/2 $\Xi$ baryon is to use two single-polarization observables, namely, the target-nucleon asymmetry $T_i$ and the recoil-$\Xi$ asymmetry $P_i$, which are defined by

$$\frac{d\sigma}{d\Omega} T_i \equiv \frac{1}{2} \text{Tr} \left( \hat{M} \sigma_i \hat{M}^\dagger \right) = 2 \text{Re} \left[ M_0 M_i^* \right] + 2 \text{Im} \left[ M_j M_k^* \right],$$

(7)

$$\frac{d\sigma}{d\Omega} P_i \equiv \frac{1}{2} \text{Tr} \left( \hat{M} \sigma_i \hat{M}^\dagger \right) = 2 \text{Re} \left[ M_0 M_i^* \right] - 2 \text{Im} \left[ M_j M_k^* \right],$$

(8)

where the subscripts $(i, j, k)$ run cyclically. Then the spin structures of the amplitudes of Eq. (1) immediately give

$$\frac{d\sigma}{d\Omega} (T_y + P_y) = 4 \text{Re} \left[ M_0 M_2^* \right], \quad \frac{d\sigma}{d\Omega} (T_y - P_y) = 0,$$

(9)

for positive-parity $\Xi$ and

$$\frac{d\sigma}{d\Omega} (T_y + P_y) = 0, \quad \frac{d\sigma}{d\Omega} (T_y - P_y) = 4 \text{Im} \left[ M_3 M_1^* \right],$$

(10)

for negative-parity $\Xi$. This can be used to determine the parity of the $\Xi(1318)$ unless $T_y \simeq P_y \simeq 0$. 

3 Summary

In summary, we have studied the spin structure of the production amplitudes in the reaction of $\bar{K}N \rightarrow KN$. We found that the spin-transfer coefficient $K_{yy}$, which is a double-polarization observable, can give a direct measurement of the parity of the $\Xi$ baryon. Furthermore, the combinations of the two single-polarization observables, the target asymmetry $T_y$ and the recoil asymmetry $P_y$, can give another way to check the parity of the produced $\Xi$. Since the $\Xi$ is self-analyzing, these asymmetries can be measured by preparing polarized nucleon targets at the current facilities like the J-PARC. Although we considered the parity of spin-1/2 $\Xi$ baryons in this article, our discussion can be generalized to the $\Xi$ of higher spin and to the polarization observables in $\Xi$ photoproduction [17]. Similar relations can be found for the determination of the parity of the $\Omega$ baryons as well.

Acknowledgements This work was partly supported by the National Research Foundation of Korea funded by the Korean Government (Grant No. NRF-2011-220-C00011). The work of K.N. was also supported partly by the FFE Grant No. 41788390 (COSY-058).

References
1. Beringer, J., et al.: The review of particle physics. Phys. Rev. D 86, 010001 (2012).
2. Nagae, T.: Spectroscopy of hypernuclei with meson beams. Lecture Notes Phys. 724, 81 (2007).
3. Nagae, T.: The J-PARC project. Nucl. Phys. A 805, 486c (2008).
4. Saitoh, T., Pochozalla, J.: Hypernuclear physics projects with PANDA at GSI. Acta Phys. Pol. B35, 1033 (2004).
5. Price, J. W., et al.: Exclusive photoproduction of the Cascade ($\Xi$) hyperons. Phys. Rev. C 71, 058201 (2005).
6. Afanasiev, A., et al.: Photoproduction of the very strangest baryons on a proton target in CLAS12. JLab. proposal (2012).
7. Guo, L., et al.: Cascade production in the reactions $\gamma p \rightarrow K^+K^+(X)$ and $\gamma p \rightarrow K^+K^-\pi^-(X)$. Phys. Rev. C 76, 025208 (2007).
8. Nakayama, K., Oh, Y., Haberzettl, H.: Photoproduction of $\Xi$ off nucleons. Phys. Rev. C 74, 035205 (2006).
9. Man, J. K. S., Oh, Y., Nakayama, K.: Role of high-spin hyperon resonances in the reaction of $\gamma p \rightarrow K^+K^+\Xi^-$. Phys. Rev. C 83, 055201 (2011).
10. Oh, Y.: $\Xi$ and $\Omega$ baryons in the Skyrme model. Phys. Rev. D 75, 074002 (2007).
11. Aubert, B., et al.: Measurement of the spin of the $\Omega^-$ hyperon at BABAR. Phys. Rev. Lett. 97, 112001 (2006).
12. Barnes, V. E., et al.: Observation of a hyperon with strangeness $-3$. Phys. Rev. Lett. 12, 204 (1964).
13. Aubert, B., et al.: Measurement of the spin of the $\Xi(1530)$ resonance. Phys. Rev. D 78, 034008 (2008).
14. Sharov, D. A., Korotkikh, V. L., Lanskoy, D. E.: Phenomenological model for the $\bar{K}N \rightarrow K\Xi$ reaction. Eur. Phys. J. A 47, 109 (2011).
15. Shyam, R., Scholten, O., Thomas, A. W.: Production of a Cascade hyperon in the $K^-$-proton interaction. Phys. Rev. C 84, 042201 (2011).
16. Bohr, A.: Relation between intrinsic parities and polarizations in collision and decay processes. Nucl. Phys. 10, 486 (1959).
17. Nakayama, K., Oh, Y., Haberzettl, H.: Model-independent determination of the parity of $\Xi$ hyperons. Phys. Rev. C 85, 042201 (2012).