Determination of Parity of Θ^+ in Polarized Proton Reaction

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The observation of the evidence of the pentaquark particle Θ^+ has triggered enormous amount of research activities both in experimental and theoretical studies of hadron physics [1, 2]. Baryons containing five or more valence quarks are totally new form of baryons. It is believed that in the early stage of the universe, matter was highly dense forming the quark matter. A natural question would then be what the mechanism is for the transition from that to the present hadronic world consisting of ordinary mesons and baryons. Understanding of multiquark states including pentaquarks will be able to answer such questions. At this moment, the existence of the pentaquarks is still the most important issue [2].

From the hadron physics point of view, the understanding of five quark systems, if they exist as quasi-stable states, will give us more information on the dynamics of non-perturbative QCD, such as confinement of colors and chiral symmetry breaking. Many ideas have been proposed attempting to explain the distinguished properties of Θ^+. However, the current theoretical situation is not yet settled at all, having revealed that our understanding of hadron physics would be much poorer than we have thought. We definitely need more solid ideas and methods to solve the related questions [2].

Turning to the specific interest in Θ^+, its relatively light mass and narrow width are the questions to be understood together with the determination of its spin and parity. In particular, the information of parity is important, since it reflects the internal motion of the constituents [3, 4, 5, 6].

Here we would like to discuss a method to determine the parity of Θ^+. In the early stage of the development, several method were proposed, but many of them were dependent on reaction mechanism, which were not suited to actual experiments [7]. It turned out, however, that a model independent method was possible using the reaction [8, 9]

$$\vec{p} + \vec{p} \to \Theta^+ + \Sigma^+ \quad \text{near threshold.} \tag{1}$$

This reaction was previously considered for the production of Θ^+ [10], but it turned out that the method provided a unique way to determine the parity. In order to extract information of parity from (1), the only requirement is that the final state is dominated by the s-wave component. The s-wave dominance in the final state is then combined with the Fermi statistics of the initial two protons and conservations of the strong interaction, establishing the selection rule: *If the parity of Θ^+ is positive, the reaction (1) is allowed at the threshold region only when the two protons have the total spin $S = 0$ and even values of relative momenta l, while, if it is negative the reaction is allowed only when they have $S = 1$ and odd l values.* This situation is similar to what was used in determining the parity of the pion [11]. Experimentally, the pure $S = 0$ state may not be easy to set up. However, an appropriate combination of spin polarized quantities allows to extract information of $S = 0$ state.

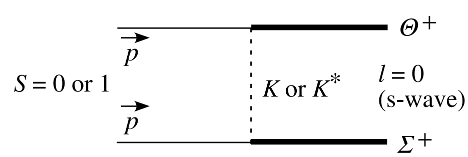

Figure 1: Born diagrams for $\vec{p}\vec{p} \to \Theta^+\Sigma+$.

In this report, we investigate production cross sections of (1). Our purposes are:

1. To check that the production reaction is indeed dominated by the s-wave (in other word, there is no accidental vanishing of s-wave contributions to invalidate the above selection rule).

2. To estimate production cross sections within the present knowledge of theoretical models.

This report is based on our previous work [9].

In order to estimate the production rate, we calculate the Born diagrams of pseudoscalar kaon ($K(498)$) and vector K^* ($K^*(892)$) exchanges, which are minimally needed for the present reaction (Fig. 1). Assuming that spin and parity of Θ^+ are $J^P = 1/2^+$, we can take effective interaction lagrangians as follows:

$$\mathcal{L}_{KN\Theta} = ig_{KN\Theta}\bar{\Theta}\gamma_5 KN + (\text{h.c.}), \tag{2}$$

$$\mathcal{L}_{KN\Sigma} = ig_{KN\Sigma}\bar{\Sigma}\gamma_5 KN + (\text{h.c.}), \tag{3}$$

$$\mathcal{L}_{K^*N\Theta} = -g_{K^*N\Theta}\bar{\Theta}\gamma^\mu K^*_\mu N + \frac{g^T_{K^*N\Theta}}{M_\Theta + M_N}\bar{\Theta}\sigma^{\mu\nu}\partial_\mu K^*_\nu N + (\text{h.c.}), \tag{4}$$

$$\mathcal{L}_{K^*N\Sigma} = -g_{K^*N\Sigma}\bar{\Sigma}\gamma^\mu K^*_\mu N + \frac{g^T_{K^*N\Sigma}}{M_\Sigma + M_N}\bar{\Sigma}\sigma^{\mu\nu}\partial_\mu K^*_\nu N + (\text{h.c.}). \tag{5}$$

with standard notations. Recently, possibilities of $J = 3/2$ is also investigated [12, 13], which is an interesting alternative to be studied in the future. If the parity of Θ^+ is negative, γ_5 matrix in (2) should be removed and in (4) γ_5 should be inserted. For the coupling terms of Σ^+, we employ the values estimated from the previous analysis; $g_{KN\Sigma} = 3.54$, $g_{K^*N\Sigma} = -2.46$ and $g^T_{K^*N\Sigma} = 1.15$ [14]. Since the couplings to the Θ^+ is not known, we investigate several cases with different parameter values. For $g_{KN\Theta}$ we employ $g_{KN\Theta} = 3.78$, which is fixed by $\Gamma_{\Theta^+\to KN} = 15$ MeV. For the unknown vector K^* couplings, we employ $|g_{K^*N\Theta}| = |g_{KN\Theta}|/2$, as suggested by Ref. [15]. The tensor couplings are then varied within $|g^T_{K^*N\Theta}| \le 2|g_{K^*N\Theta}| = |g_{KN\Theta}|$ in order to see model dependence of this process. As for the form factor, we employ the following form of the monopole type:

$$F(q^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}, \tag{6}$$

where q^2 is the four momentum square and m the mass of the exchanged particle (either K or K^*). The cut off parameter Λ is chosen to be $\Lambda = 1$ GeV. In Ref. [16] the authors employed a different type of form factor. However, the monopole type is more often used for meson-baryon vertices. In any events, the main points in the following discussions will not be changed by the use of different form factors.

The calculation for the scattering amplitude is straightforward once having the interaction, Eqs. (2) $\sim$ (5). In Fig 2, total cross sections near the threshold region are shown as functions of the energy in the center of mass system $\sqrt{s}$ ($\sqrt{s}_{\rm th} = 2729.4$ MeV). The left (right) panel is for the positive (negative) parity Θ^+ where the allowed initial state has $S = 0$ and even l ($S = 1$ and odd l). For the allowed channels, five curves are shown using different coupling constants of $g_{K^*N\Theta}$ and $g^T_{K^*N\Theta}$; zero and four different combinations of signs with the absolute values $|g^T_{K^*N\Theta}| = 2|g_{K^*N\Theta}| = |g_{KN\Theta}|$, as indicated by the pair of labels in the figures, (sgn($g_{K^*N\Theta}$), sgn($g^T_{K^*N\Theta}$)). As shown in the figure, cross sections vary within about 50 % from the mean value. For the forbidden channels only the case of vanishing $K^*N\Theta$ coupling constants is shown; cross sections using finite coupling constants vary within about 50 % just as for the allowed channels. In both figures, the s-wave threshold behavior is seen for the allowed channels as proportional to $(s - s_{th})^{1/2}$, while the forbidden channels exhibit the p-wave dependence of $(s - s_{th})^{3/2}$ and with much smaller values than the allowed channel. The suppression factor is given roughly by [(wave number)$\cdot$(interaction range)]$^2 \sim k/m_K \sim 0.1$ ($k = \sqrt{2m_K E}$), as consistent with the results shown in the figures.

From these results, we conclude that the absolute value of the total cross section is of the order 1 [μb] for the positive parity Θ^+ and of the order 0.1 [μb] for the negative parity Θ^+. The fact that the positive parity case has larger cross section is similar to what was observed in the photoproduction and hadron induced reaction also [7]. This is due to the p-wave nature of the $KN\Theta$ coupling with a relatively large momentum transfer for the Θ^+ production. When the smaller decay width of Θ^+ is used, the result simply scales as proportional to the width, if the $K^*N\Theta$ couplings are scaled similarly.

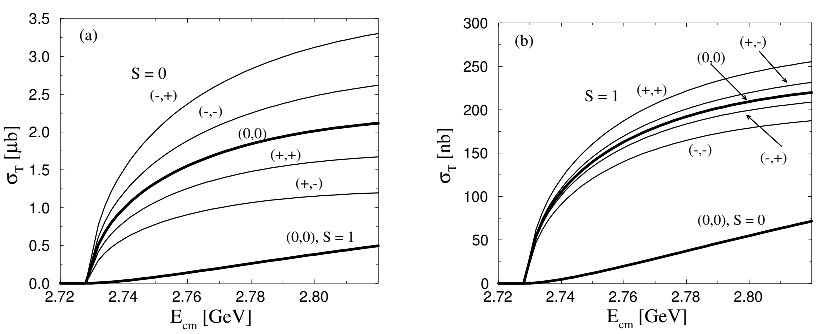

Figure 2: Total cross sections near the threshold: (a) for positive parity Θ^+ where the allowed channel is $S = 0$ and (b) for negative parity Θ^+ where the allowed channel is $S = 1$. The labels (+,+) etc denote the signs of $g_{K^*N\Theta}$ and $g^T_{K^*N\Theta}$ relative to $g_{KN\Theta}$. The solid lines in the bottom is the cross sections for the forbidden channels.

In Fig. 3, we show the angular dependence in the center of mass system for several different energies above the threshold, $\sqrt{s} = 2730$, 2740, 2750 and 2760 MeV. Here only K exchange is included but without K^*

exchanges. The angular dependence with the K^* exchanges included is similar but with absolute values scaled as in the total cross sections. Once again, we can verify that the s-wave dominates the production reaction up to $\sqrt{s} \lesssim 2750$.

Recently, in Ref. [17, 18], the authors discussed the experimental methods and observables to determine the parity of the Θ^+ baryon with the polarized proton beam and target. They discussed the spin correlation parameter A_{xx} as well as cross sections. It is computed by

$$A_{xx} = \frac{(^3\sigma_0 + ^3\sigma_1)}{2\sigma_0} - 1, \tag{7}$$

where σ_0 is the unpolarized total cross sections and the polarized cross section are denoted as $^{2S+1}\sigma_{S_z}$. In Fig. 4 we present A_{xx} where we do not include K^* exchange, but the results do not change very much by including K^*. As shown in the figures A_{xx} reflects very clearly the differences of the parity of Θ^+. The cases with and without the form factor are similar and well fall into the region as indicated in Ref. [17].

In actual experiment, it is necessary to detect Σ also at the threshold region. Due to small energy (or velocity) of the final state particles in the center of system, produced Σ must be detected inside a very narrow cone forward peaked in the laboratory frame. Because of this fact, measurement at the existing facility of fixed target, such as COSY, would require an experimental challenge.

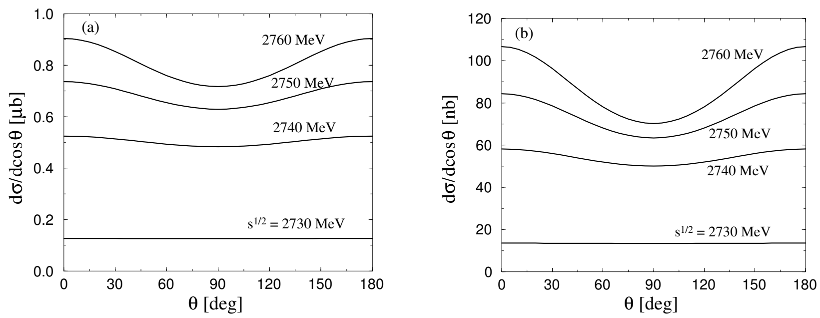

Figure 3: Angular dependence of the production cross sections near the threshold in the center of mass frame: (a) for positive parity Θ^+ and (b) for negative parity Θ^+. The labels denote the total incident energy $\sqrt{s}$.

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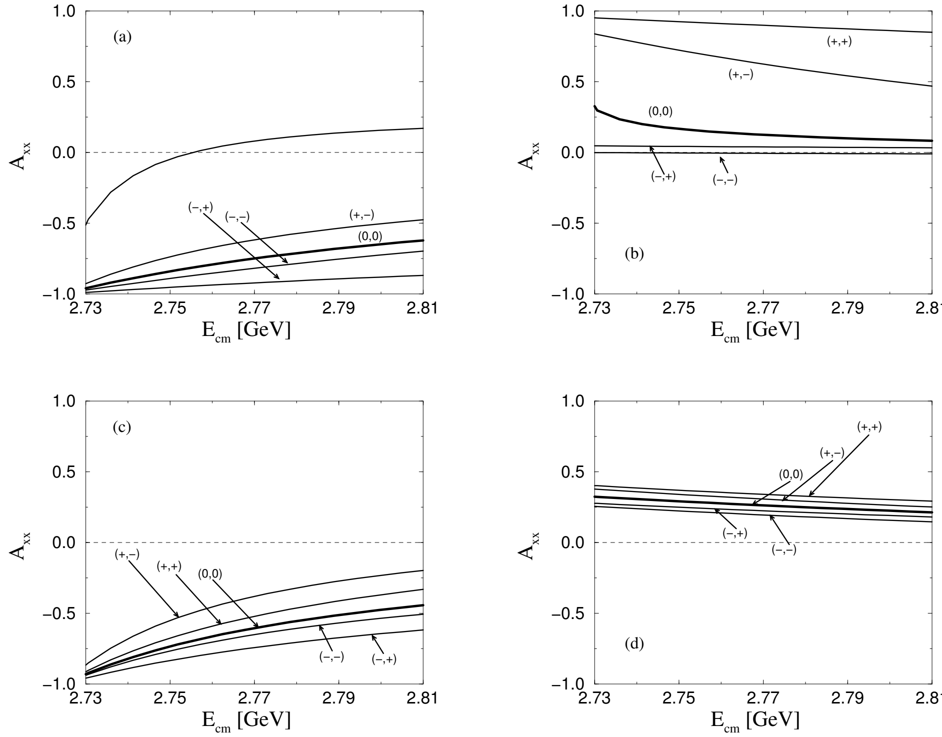

Figure 4: A_{xx} for the positive (a) and negative (b) parities are drawn without the form factor. As for the cases with the form factor, we also show it for the positive (c) and negative (d) parities.

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