Inclusive pentaquark and strange baryons production in hadron beam experiments at high energy

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Abstract. We estimate the high-energy behavior of the $\Theta^+$ and $\Lambda(1520)$ production cross sections in inclusive $pp$ collisions using the $K$ exchange diagram. We show that the cross section of the $\Theta^+$-production is suppressed compared to the production of $\Lambda(1520)$. As a byproduct we also estimate the contribution of the $\pi$ exchange diagram for the inclusive $\Lambda(1520)$ production in $\Sigma p$ collisions.

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1 Introduction

The possible existence of the $\Theta^+$ pentaquark remains one of the puzzling mysteries of recent years. To date there are more than 20 experiments with evidence for this state, but criticism for the $\Theta^+$ claim arises because similar number of high energy experiments did not find any evidence for the $\Theta^+$, even though the other “conventional” three-quark hyperons such as $\Lambda(1520)$ hyperon resonance are seen clearly [1].

Most of negative high energy experiments are high statistic hadron beam experiments. E.g. HERA-B, a fixed target experiment at the 920 GeV proton storage ring of DESY [2] finds no evidence for narrow signals in the $\bar{K}^0 p$ channel and only sets modest upper limits for $\Theta^+$ production of less than 16 $\mu b/N$ and less than about 12% relative to $\Lambda(1520)$ in mid-rapidity region. This negative result would present serious rebuttal evidence to worry about. However, without obvious production mechanism of the $\Theta^+$ (if it exists) or even $\Lambda(1520)$ the rebuttal is not very convincing.

In this paper we estimate the high-energy behavior of the $\Theta^+$ and $\Lambda(1520)$ production cross sections in inclusive $pp$ collisions using the $K$ exchange diagram, which is known to survive at high energies in the beam/target fragmentation region. We show that the cross section of the $\Theta^+$-production is suppressed compared to the production of $\Lambda(1520)$. This suppression is mainly due to the smallness of the coupling constant $G_{\Theta KN}^2$ compared to $G_{\Lambda KN}^2$ that in turn is related to the small width of the $\Theta^+$. As a byproduct we also estimate the contribution of the $\pi$ exchange diagram for the inclusive $\Lambda(1520)$ production in $\Sigma p$ collisions.

2 Inclusive cross sections

We assume that the $\Theta^+$ exists and $J^P(\Theta^+)=\frac{1}{2}^+$. Consider the $\Theta^+$ production in the reaction $p+p\rightarrow \Theta^+ +X$, where $X$ is unspecified inclusive final state carrying the strangeness -1. The $\bar{K}^0$ exchange diagram for $pp \rightarrow \Theta^+ X$ is shown in Fig. 1.

The standard expression for the contribution of this diagram written in terms of the 4-momentum transfer squared $t=q^2$ and the invariant mass $W$ of the $K^0p$ system is well known [3]. At high energy, it is more convenient to convert this expression to an integral over the Feynman variable $x_F$, the fraction of the incident proton momentum carried by the $\Theta^+$ in the initial direction of the proton (in the center-of-mass system), and $k_\perp$, the transverse momentum of $\Theta^+$ relative to the initial proton direction. Then the contribution of the $K$ meson exchange to the double differential cross section for the $\Theta^+$ inclusive production reads

$$\frac{d^2\sigma}{dx_Fdk_\perp^2} = \frac{1}{4\pi} \frac{G_{\Theta KN}^2}{4\pi} J \frac{p}{E_\Theta} F(p) F^*(s) \sigma_{tot}(s_1),$$

where $G_{\Theta KN}$ is the coupling constant for the decay $\Theta^+ \rightarrow \bar{K}^0 p$, $E_\Theta = \sqrt{x_F p^2 + k_\perp^2 + m_\Theta^2}$ is the $\Theta^+$ energy in the
center-of-mass system, \( s_1 = W^2 = s + m_0^2 - 2E_\Theta \sqrt{s} \), \( s = 4(p^2 + m_0^2) \) is the center-of-mass energy squared, \( p \) is the center-of-mass momentum, and \( t = m_0^2 + m_0^2 - 2E_\Theta \sqrt{p^2 + m_0^2 + 2xp^2} \). The factor \( J \) is the ratio of flux factors in the \( pp \) and \( K^0 \) reactions. To evaluate the cross sections away from the pole position \( t = M_K^2 \) we include the phenomenological form factor \( F_K(t) \). The function \( \Phi_\Theta(t) \) is the squared product of the vertex function for \( p \rightarrow \Theta^+ K^0 \) and the kaon propagator:

\[
\Phi_\Theta(t) = \frac{(m_p - m_0)^2 - t}{(t - m_K^2)^2}, \tag{2}
\]

In the high energy limit with accuracy \( O(1/p^2) \)

\[
J \cdot \frac{p}{E_\Theta} \approx \frac{1 - x_F}{x_F}, \tag{3}
\]

\( s_1 \approx (1 - x_F)s, \ t \approx m_0^2 + m_p^2(1 - x_F) - \frac{m_0^2 + k_2^2}{x_F} \tag{4} \)

and the double differential cross section written in terms \( x_F \) and \( k_2^2 \) reads

\[
\frac{d\sigma}{dx_F dk_2^2} = \frac{1}{4 \pi} \frac{G^2_{\Theta KN}}{4 \pi} \frac{1 - x_F}{x_F} \Phi_\Theta(t) F^4(t) \sigma_{\text{tot}}(s_1). \tag{5}
\]

### 2.1 The \( \Theta^+ KN \) vertex

The \( \Theta^+ KN \) vertex is

\[
L_{\Theta KN} = ig_{\Theta KN}(K^+ \tilde{\Theta} \gamma_5 N + \tilde{N} \gamma_5 \Theta K), \tag{6}
\]

with the operator \( \gamma_5 \) corresponding to positive \( \Theta^+ \) parity. The Lagrangian (6) corresponds with the \( \Theta^+ \) being a \( p \)-wave resonance in the \( K^0p \) system. The partial decay width \( \Gamma_{\Theta \rightarrow K^0p} \) is

\[
\Gamma_{\Theta \rightarrow K^0p} = \frac{G^2_{\Theta KN}}{4 \pi} \left( \frac{2 p_K^2}{(m_0 + m_p)^2 - m_K^2} \right), \tag{7}
\]

where \( p_K = 260 \text{ MeV}/c \) is the kaon momentum in the rest frame of \( \Theta^+ \). To extract the value for \( G_{\Theta KN} \), we need the experimental information of the width \( \Gamma_{\Theta KN} \), which is not known precisely but whose measurement is the subject of several planned dedicated experiments. To provide numerical estimates, we will use the value \( \Gamma_{\Theta \rightarrow K^0p} = 1 \text{ MeV} \). This corresponds to the full width \( \Gamma_{\Theta KN} = \Gamma_{\Theta \rightarrow K^0p} + \Gamma_{\Theta \rightarrow K^0n} = 2 \text{ MeV} \), which is consistent with the upper limit for the width derived from elastic \( K \) scattering \[4\] \[5\].

1. An additional reason for the smallness of the pentaquark width arises in the string model, in which the pentaquark decay is accompanied by the annihilation of the two string junctions. Indeed, the pentaquark containing three string junctions dissociates “full apart” into two minimal color singlets containing only one string junction. The annihilation of the string junctions may produce a complimentary smallness of the width.

Evaluating Eq. (7) with \( \Gamma_{\Theta \rightarrow K^0p} = 1 \text{ MeV} \), we extract the value \( G^2_{\Theta KN} = 0.167 \text{ GeV}^{-1} \text{ MeV}^{-1} \), which will be used in the subsequent estimates for the inclusive cross section.

### 2.2 \( \Lambda(1520) \) \( KN \) vertex

The \( \Lambda(1520) \) \( KN \) vertex is

\[
L_{\Lambda KN} = \frac{G_{\Lambda KN}}{m_K} (\bar{A}_\mu \gamma_\nu N \partial_\nu K + \bar{N} \gamma_\nu A^\mu \partial_\mu K^1), \tag{9}
\]

where \( A^\mu \) is the vector spinor for the spin 3/2 particle. The Lagrangian (10) corresponds with the \( \Lambda(1520) \) being a \( d \)-wave resonance in the \( K^-p \) system. The \( \Lambda(1520) \rightarrow pK^- \) width is

\[
\Gamma_{\Lambda \rightarrow K^-p} = \frac{G^2_{\Lambda KN}}{4 \pi} \left( \frac{2 p_K^5}{3m_K^2} \right) \left( \frac{1}{m_A + m_p} \right), \tag{10}
\]

where \( p_K = 246 \text{ MeV}/c \) is the kaon momentum in the rest frame of \( \Lambda(1520) \). Using the PDG values of \( \Gamma_{\text{tot}}(\Lambda(1520)) = 15.6 \text{ MeV} \) and \( \text{Br}(\Lambda(1520) \rightarrow NK) = 45\% \) we obtain

\[
G^2_{\Lambda KN} = \frac{4 \pi}{8.14}. \tag{11}
\]

The function \( \Phi_{\lambda A}(t) \) is

\[
\Phi_{\lambda A}(t) = \frac{1}{6m_A^2 m_K} (m_A - m_p)^2 - \frac{(m_A^2 + m_p^2 - t)^2}{(t - m_K^2)^2}, \tag{12}
\]

The expression (12) includes the factor \( 1/m_K \) in (3).

### 3 Results

The total cross section for the general case of the fragmentation of a baryon \( a \) into a baryon \( b \) due to the exchange by the meson \( m \) is

\[
\sigma_{ab} = \frac{G^2_{2m_a}}{4 \pi} \int dx_F \int dk_2^2 K_{ab}(x_F, k_2^2) \sigma_{\text{tot}}^{mp}(s_1), \tag{13}
\]

where \( K_{ab}(x_F, k_2^2) = (1 - x_F) F_{ab}(t) F^4(t)/x_F \). We employ two representative examples for the form factor \( F(t) \):

\[ A : F(t) = \frac{A^2 - m_K^2}{A^2 - t}, \quad B : F(t) = \frac{A^4}{A^4 + (t - m_K^2)^2}. \]

the cut-off parameter \( A \) being a typical hadronic scale \( A = 1 \text{ GeV} \).

Because of (3), (4) all the energy dependence of the right hand side of Eq. (3) is due to the factor \( \sigma_{mp}^{\text{tot}}(s_1) \). Since \( \sigma_{mp}^{\text{tot}}(s_1) \) is slow varying function of \( s_1 = (1 - x_F)s \) everywhere, except the low energy region, we can take it
out of the integral at the point $\hat{s}_1 = (1 - \hat{x}_F)s$, where $\hat{x}_F$ is the point at which $d\sigma^{\text{mp}} / dx_F$ reaches the maximum.$^4$

Then we obtain

$$\sigma_{ab} \approx \frac{G^2_{\text{uni}}}{4\pi} \sigma^{\text{mp}}_{\text{tot}}(\hat{s}_1) \tilde{K}_{ab},$$

where the quantities

$$\tilde{K}_{ab} = \int dx_F \int dk^2_\perp K_{ab}(x_F, k^2_\perp)$$

do not depend on energy, and $\sigma^{\text{mp}}_{\text{tot}}(\hat{s}_1)$ is a constant up to logarithmic and power corrections.

For estimation we take the total cross sections $\sigma^{\text{mp}}_{\text{tot}}$ and $\sigma^{K^+p}_{\text{tot}}$ to be a constant ($\sigma^{K^+p}_{\text{tot}} \approx \sigma^{\text{mp}}_{\text{tot}} \approx 20 \text{ mb at } \sqrt{s} > 10 \text{ GeV}$.) Then we obtain for the production cross sections

$$\sigma(pp \to \Theta^+(1540)X) = 0.8 \times (1.6) \times \frac{\Gamma_{\Theta^+ \to K^+p}}{1 \text{ MeV}} \mu\text{b}, \quad (16)$$

$$\sigma(pp \to \Lambda^+(1520)X) = 106 \times (126) \mu\text{b}, \quad (17)$$

where the first values refer to the form factor (A) and the second ones to the form factor (B). The result for $\sigma(pp \to \Theta^+X)$ matches well that of Ref. [6] for the inclusive $pp \to \Theta^+X$ production at $\sqrt{s} < 10 \text{ GeV}$. If $\Gamma_{\Theta K_N} = 0.36 \pm 0.11 \text{ MeV}$ as is claimed in [7], our result for the $\Theta^+$ production cross section should be correspondingly smaller.

In scattering hadronic probes at high energy from nuclear target the only positive signal for the $\Theta^+$ decaying to $K_S^0p$ was reported by the SVD Collaboration, using 70 GeV proton in a fixed target arrangement $pA \to \Theta^+X$ at a center-of-mass energy of about 11.5 GeV [6]. Our prediction for $\sigma(pp \to \Lambda(1540)^+X)$ agrees with the preliminary result of the SVD-2 collaboration, but $\sigma(pp \to \Theta^+X)$ is lower than the preliminary cross section estimation (for $x_F > 0$): $\sigma \cdot \text{Br}(\Theta^+ \to pK^0) \sim 6 \mu\text{b}$. The illustrative examples of the $x_F$ distributions for the $\Theta^+$ and $\Lambda(1520)$ are shown in Fig. [2] for the form factor A.

The ratio of $\Theta^+$ to $\Lambda(1520)$ production cross-sections is $\sim 1\%$. Our estimation is a bit larger than that of the preliminary cross section estimation (for $pp \to \Lambda(1520)^+X$) at 600 GeV/c$^2$.

studied in the fixed target Fermilab experiment E781 (SELEX). In the fragmentation region of the $\Sigma$-hyperon this reaction can proceed via the $\pi$-meson exchange. Using

$$\Gamma_{A \to \pi^- \Sigma^+} = \frac{1}{3} \cdot \text{Br}(\Lambda \to \pi \Sigma) \cdot \Gamma_{\text{tot}} = 2.18 \text{ MeV}, \quad (18)$$

$$G^2_{A \pi \Sigma}/4\pi \approx 0.353, \text{ and } \sigma(\pi N) = 25 \mu\text{b we get} \quad$$

$$\frac{\sigma(\Sigma p \to \Lambda(1520)X)}{\sigma(pp \to \Lambda(1520)X)} \approx 2.9 (2.7), \quad (20)$$

that agrees with the preliminary experimental result ($\approx 2.6$) of the SELEX collaboration [9].

4 Conclusions

Let us recall that our estimations may somehow depend on specific assumptions regarding for instance the $K$-meson exchange dominance at forward direction, and on the choice of the form factor. As an outlook, it would be interesting to go beyond the present calculation and to perform a systematic study of $K$, $K^*$ and $\pi$ Regge exchanges into inclusive production of (anti)strange baryons in $pp$ collisions. We plan to come back to these issues in a next publication.

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