Abstract

We estimate the cross sections for the inclusive production of $\Theta^+$ and $\Lambda(1520)$ in $pp$ collisions at high energy using the $K$ exchange diagrams. We find that inclusive $\Theta^+$ production should be at the level of $1 \, \mu b$ at energies $\sqrt{s} \gtrsim 10$ GeV. The ratio of $\Theta^+(1540)$ to $\Lambda(1520)$ production cross-sections is $\sim 1\%$.

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 “conventional” three-quark hyperons states, such as $\Lambda(1520)$ resonance, are seen clearly$^1$. The superposition of positive and negative results is very disturbing. New experiments are needed to confirm or refute pentaquark existence.

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 the upper limit on production $\Theta^+$ and $\Lambda(1520)$

$^1$The situation is getting more intriguing, as recently CLAS collaboration reported negative results on $\Theta^+$ photoproduction off proton and deuteron with high statistics. Meanwhile LEPS collaboration reported the new evidence of the $\Theta^+$ in $\gamma d \rightarrow \Theta^+ \Lambda^*(1520)$. Also, STAR collaboration observed the doubly charged exotic baryon in the $pK^+$ decay channel. For a recent review see [1].
cross sections in mid-rapidity region. This negative result would present serious rebuttal evidence to worry about. However, without obvious production mechanism of the Θ\(^+\) (if it exists) or even Λ(1520) the rebuttal is not very convincing. As of today, the only positive high-energy hadron beam result is that by SVD Collaboration [3] who finds a narrow \(K_0^0\) resonance in the inclusive \(pA \rightarrow \Theta^+X\) reaction using 70 GeV proton beam at IHEP accelerator.

In this paper we estimate the high-energy behavior of Θ\(^+\) and Λ(1520) production in inclusive \(pp\) processes in the fragmentation region using the \(K\)-exchange diagrams. Our conclusion is that the cross section of the \(Θ^+\)-production is suppressed compared to the production of \(Λ(1520)\) by a factor of \(~10^{-2}\). This suppression is mainly due to smallness of the coupling constant \(G_{ΘKN}^2\) compared to \(G_{ΛKN}^2\) that in turn is related to the small width of the \(Θ^+\).

2 Inclusive production cross sections

The \(K^0\)-exchange diagram for \(pp \rightarrow Θ^+X\) is shown in fig. [4]. In the high energy limit the corresponding cross section written in terms of the Feynman variable \(x_F\), the fraction of incident proton momentum carried by the \(Θ^+\) (in the center-of-mass system), and \(k_\perp\), the transverse momentum of the \(Θ^+\) relative to the initial proton momentum, reads

\[
\frac{d\sigma}{dx_F dk_\perp^2} = \frac{1}{4\pi} \cdot \frac{G_{ΘKN}^2}{4\pi} \cdot \frac{1 - x_F}{x_F} \cdot \Phi_Θ(t) \cdot F^4(t) \cdot \sigma_{\bar{K}N}(s_1),
\]

where \(s_1 = (1 - x_F)s\), \(s = 4(p^2 + m_p^2)\) is total center-of-mass energy squared, \(F(t)\) is the phenomenological form factor, \(t\) is the 4-momentum transfer squared, and \(\Phi_Θ(t)\) is the squared product of the vertex function for \(p \rightarrow Θ^+\bar{K}^0\) and kaon propagator:

\[
\Phi_Θ(t) = \frac{(m_N - m_Θ)^2 - t}{(t - m_K^2)^2}.
\]

At high energy

\[
t \approx m_Θ^2 + m_p^2(1 - x_F) - \frac{m_Θ^2 + k_\perp^2}{x_F},
\]

and the total cross section is energy independent.

The cross section for the inclusive \(Λ(1520)\) production has the similar form with the substitutions

\[
G_{ΘKN} \rightarrow G_{ΛKN}, \quad \Phi_Θ \rightarrow \Phi_Λ = \frac{(m_Θ + m_Λ)^2 - t}{6m_Θ^2m_Λ^2} \cdot \frac{(m_p - m_Λ)^2 - t}{(t - m_Λ^2)^2},
\]
2.1 The $KN\Theta^+$ vertex

The $KN\Theta^+$ vertex for $J^P(\Theta^+) = \frac{1}{2}^+$ is

$$L_{\Theta KN} = iG_{\Theta KN}(K^+\bar{\Theta}\gamma_5N + \bar{N}\gamma_5\Theta K).$$

(5)

The Lagrangian of Eq. (5) corresponds with the $\Theta^+$ being a $p$-wave resonance in the $K^0p$ system. The partial decay width $\Gamma_{\Theta \to K^0p}$ is

$$\Gamma_{\Theta \to K^0p} = \frac{G_{\Theta KN}^2}{4\pi} \cdot \frac{2p_K^3}{(m_\Theta + m_p)^2 - m_K^2},$$

(6)

where $p_K = 260$ MeV/c is the kaon momentum in the rest frame of $\Theta^+$. The coupling constant $G_{K\Theta\Omega}$ can be expressed through the $\Theta^+$ width as

$$\frac{G_{\Theta KN}^2}{4\pi} = 0.167 \cdot \frac{\Gamma_{\Theta \to K^0p}}{1\text{ MeV}}.$$  

(7)

2.2 $K\Lambda(1520)$ vertex

The $K\Lambda(1520)$ vertex is

$$L_{\Lambda KN} = \frac{G_{\Lambda KN}}{m_K} (\bar{\Lambda}\gamma_5N\partial_\mu K + \bar{N}\gamma_5\Lambda^\mu\partial_\mu K^+) ,$$

(8)

where $\Lambda^\mu$ is the vector spinor for the spin 3/2 particle. The Lagrangian of Eq. (8) corresponds with the $\Lambda(1520)$ being a $d$-wave resonance in the $K^-p$ system. The $\Lambda(1520) \to pK^-$ width is

$$\Gamma_{\Lambda \to K^-p} = \frac{G_{\Lambda KN}^2}{4\pi} \cdot \frac{2p_K^5}{3m_K^2} \cdot \frac{1}{(m_\Lambda + m_p)^2 - m_K^2} .$$

(9)

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

$$\frac{G_{\Lambda KN}^2}{4\pi} \approx 8.14 .$$

(10)
Figure 2: $x_F$ (left) and $k_\perp$ (right) dependence of inclusive cross sections

3 Results

The inclusive cross sections can be obtained by integrating (11) over $k_\perp$ and $x_F$ considering the total cross sections $\sigma_{tot}(\bar{K}^0 p)$ and $\sigma_{tot}(K^- p)$ as constants ($\sigma_{tot}(\bar{K}^0 p) \sim \sigma_{tot}(K^- p) \sim 20$ mb). We take two representative examples for the form factor $F(t)$ in (11):

$$F(t) = \frac{\Lambda^2 - m_K^2}{\Lambda^2 - t} \quad \text{(choice A)}$$

and

$$F(t) = \frac{\Lambda^4}{\Lambda^4 + (t - m_K^2)^2} \quad \text{(choice B)} \quad (11)$$

with $\Lambda = 1$ GeV. Then we obtain for the production cross sections

$$\sigma(pp \rightarrow \Theta^+ X) = 0.8 \ (1.6) \times \frac{\Gamma_{\Theta KN}}{1 \text{ MeV}} \mu b, \quad \sigma(pp \rightarrow \Lambda(1520)^+ X) = 106 \ (126) \ \mu b, \quad (12)$$

where the first values refer to the form factor (A) in (11) and the second ones to the form factor (B). The result for $\sigma(pp \rightarrow \Theta^+ X)$ matches well that of Ref. [4] for the inclusive $pp \rightarrow \Theta^+ X$ reaction at the threshold and intermediate energies. One can expect that the $K^*$ exchange yields the cross sections of the similar order of magnitude.

Our prediction for $\sigma(pp \rightarrow \Lambda(1520)^+ X)$ agrees with the preliminary result of the SVD-2 collaboration [3], but $\sigma(pp \rightarrow \Theta^+ X)$ is lower than the preliminary cross section estimation (for $x_F > 0$) of Ref. [3]: $\sigma \cdot BR(\Theta^+ \rightarrow pK^0) \sim 6 \ \mu b$.

The $x_F$ distributions and transverse momentum distributions for the $\Theta^+(1540)$ and $\Lambda(1520)$ are shown in Fig. 2. For the average transfer momenta squared of $\Theta^+$ and $\Lambda(1520)$ we get

$$< k_\perp^2 > = 0.25 \text{ GeV}^2 \quad \text{and} \quad < k_\perp^2 > = 0.25 \text{ GeV}^2, \quad (13)$$

respectively.
The ratio of $\Theta^+(1540)$ to $\Lambda(1520)$ production cross-sections is $\sim 1\%$. Probably today our calculations can be useful to explain why the $\Theta^+$ production is suppressed in some high energy experiments.

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